Economic and Fuel Performance Analysis of Extended Operating Cycles in Existing Light Water Reactors (LWRs)

by

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B. S., Systems Engineering
United States Naval Academy, 1996

Submitted to the Department of Nuclear Engineering and
the Technology and Policy Program
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Nuclear Engineering

and

Master of Science in Technology and Policy

at the Massachusetts Institute of Technology
June 1998

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ABSTRACT

SECTION I: Economic Analysis of Extended Operating Cycles in Existing LWRs

The generic economic aspects of extending operating cycles in LWRs are examined to assess the factors associated with cycle lengths at or near the limit of technical feasibility, based on current NRC-mandated burnup limits. These factors are broken into 2 basic categories, Fuel Cycle Economic Factors and Operations and Maintenance (O&M) Economic Factors. Results are evaluated relative to current practice: 18 calendar month cycles refueling 72 of 193 assemblies each shutdown for the case study PWR and 24 month cycles refueling 255 of 764 assemblies each shutdown for the case study BWR, both with a 6% Forced Outage Rate (FOR) and 49 day Refueling Outage (RFO). Tallying all of the realizable factors, it is evident that large fuel cycle costs will be incurred as a result of cycle length extension. Thus, large savings in O&M must be realized to make ultra-long cycles economically attractive. Quantifying these factors, it is shown that cycle length extension to 48 calendar months (with a RFO length of 42 days and FOR of 3%) incurs a significant deficit for the case study BWR (**~$8.9M/yr.**) and cycle length extension to 41.4 calendar months (with a RFO length of 42 days and FOR of 3%) yields a profit of approximately **$1.0M/yr.** for the case study PWR.

A simple model is also constructed and applied to find the economically optimum cycle length. This model employs only five basic factors: increased fuel costs, increased spent fuel storage costs, savings from avoided refueling outages, savings from a reduced forced outage rate and replacement energy savings; all others are considered either constant regardless of length of cycle extension, or insignificant. This model shows that multi-batch fuel management is more profitable than single batch management for cycle lengths shorter than ultra-long cycles, i.e. 63 calendar months for the case study BWR and 48 calendar months for the case study PWR. The most profitable strategy at which to operate both of these plants was found to be at or near current practice: n=3, 24 calendar month cycles for the case study BWR and n=3, 18 calendar months cycles for the case study PWR. The economically optimum strategy predicted for the case study PWR violated current burnup limits, suggesting a need to re-evaluate these limits as a means of improving plant economics. Additionally, since these current practice strategies that were evaluated using this model were awarded the same operational benefits as the extended operating cycles and were found to be less costly, investing in improving the operations of current nuclear power plants is a more economically viable option than cycle length extension.

Parametric studies are performed using this model to vary important parameters such as replacement energy costs, carrying charge rate, unit enrichment costs, and operational parameters. Increasing replacement power costs not only increases the cost of extending cycle length, but also increases the optimum cycle length. For increased carrying charge rate, cost increases, while optimum cycle length decreases. Additionally, the sensitivity of cost to carrying charge rate increases with cycle length. Lower enrichment costs not only decrease the cost of a particular operating strategy, but also significantly increase the optimum cycle length. Finally, the sensitivity of the cost of an operating strategy to its respective

operational parameters (FOR, RFO) decreases with increasing cycle length; optimum cycle length also increases with poorer operational characteristics.

The significant effect of unit enrichment costs on an operating cycle's total cost shows that innovations in enrichment technologies are essential for making extended operating cycles economically competitive. The increase in the volume of spent nuclear fuel that is generated by extending operating cycle length is also an area that requires further consideration in order to make this strategy more attractive. Extending burnup limits to realize the full economic potential of long cycle operation, especially in the case study PWR, is also an area deserving future investigation.

SECTION II: Fuel Performance Analysis of Extended Operating Cycles in Existing LWRs

An integral part of a technical analysis of a core design, fuel performance is especially important for extended operating cycles since the consequences of failed fuel are greater for this operating strategy than for current practice. This stems mainly from the fact that extended cycles offer a unique benefit by running longer without interruption; poor fuel performance, i.e. failed fuel, would degrade this benefit.

The issues in this research are assessed only at the steady-state level, as a foundation for the consideration of Anticipated Operational Occurrences (AOOs) and transient conditions, which are certain to present greater challenges to nuclear fuel performance due to their more severe conditions. Even at this preliminary steady state level, extended cycle operation is found to exacerbate several fuel performance issues, resulting mainly from the fact that some fuel in an extended operating cycle is operated at higher powers over part of the core life and does not have the benefit of shuffling.

In order to accurately quantify the fuel performance effects of extended cycle operation, a pseudo or "envelope" pin is created, which represents the operating characteristics of the highest power fuel rod in the core at a given pin burnup interval. This envelope pin was created for both extended cycle and current practice, so that extended cycle results could be compared to both existing licensing limits and current practice. While this approach is somewhat conservative, it is the simplest way to evaluate fuel performance in an extended cycle core where the location of the limiting fuel rod changes often and operates at higher powers for prolonged periods of time.

The US Nuclear Regulatory Commission's Standard Review Plan's Sections 4.2 and 4.4 are used as the basis for the criteria that should be evaluated in this report, since these are the relevant sections of the document that prescribes the licensing limits and criteria for nuclear fuel design. From this document, ten steady state fuel performance issues are identified: (1) stress and strain, (2) fatigue cycling, (3) fretting, (4) waterside corrosion, (5) axial growth and rod bowing, (6) rod internal pressure, (7) primary hydriding, (8) cladding collapse, (9) cladding overheating, and (10) fuel centerline melt. Of these ten issues, (7) and (8) were found to be not uniquely affected by extended cycle operation. While (9) and (10) are found to not be concerns for extended cycle operation, the higher powers at which extended operating cycles can operate degrade some of the margin for transient effects, which is more of a significant concern for (9). (1) and (5) are predicted to be worse for both BWRs and PWRs when compared to current practice, and (4) and (6) are projected to present greater challenges for PWRs. Additionally, (2) is the only factor that is predicted to actually be better for extended cycle operation in both the BWR and PWR while (4) was predicted to have less of an effect in BWRs, given the comparable operating powers and shorter in-core residence time for the extended cycle case. The effects of the proposed new operating strategy on (3) were uncertain.

Of all ten issues, (5) seemed to be the most problematic, as no solution was readily available. Solutions to other issues included improved assembly grid design (3), water chemistry control (4), annular fuel pellets (6), and, potentially, increasing the number of fuel rods per assembly (1,4,6,10).

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Acknowledgments

This project has been funded by the Idaho National Engineering and Environmental Laboratory (INEEL) University Research Consortium. The INEEL is managed by Lockheed Martin Idaho Technologies Company for the U. S. Department of Energy, Idaho Operations Office, under Contract No.DE-AC07-94ID13223.

Special thanks must be given to industry collaborators for their assistance with this project, especially to Dr. Ed Pilat, Kevin St. John, and Dr. John Chun of the Yankee Atomic Electric Company.

Additionally, the author wishes to thank his colleagues, specifically Michael McMahon, and the faculty in the Nuclear Engineering Department at MIT for their time, energy, patience, and help in providing the valuable assistance that made this report possible. The author is especially appreciative of the feedback provided by Professor Richard Lester for the policy chapter.

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SECTION I: Economic Analysis of Extended Operating Cycles in Existing LWRs

Chapter 1: INTRODUCTION

1.1 Foreword

Increased competitive pressures arising from deregulation of the U. S. energy market have caused the nuclear power industry to seek ways to cut energy production costs. One approach is to increase capacity factor by extending the length of the intra-refueling operating cycles of nuclear power plants. Since U. S. plants are base loaded, that is they run at maximum capacity whenever possible, capacity factor will be used as the metric for all comparisons throughout this work since it most accurately represents revenue generating capability. This and other terms are explicitly defined in Section 1.4.

Capacity factor, defined as the ratio of the actual electrical energy produced to the amount of electrical energy which could have been produced by operating the plant at 100% power over a given time period, is a function of three variables: forced outage rate (FOR), planned outage time, T_P (comprised mainly of the refueling outage length, T_R or RFO), and cycle length, T_C, as follows (see Appendix C for derivation of formulae and how these metrics are defined relative to other industry plant performance criteria):

$$L = L'\left(1 - \frac{T_P}{T_C}\right) \qquad \{1\text{-}1\}$$

where: L = Capacity Factor

L' = 1 minus Forced Outage Rate = Availability

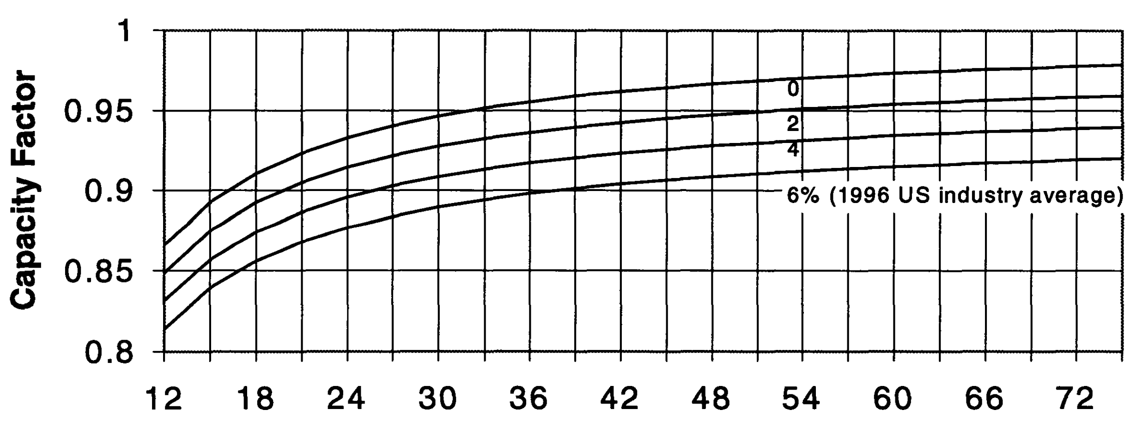
T_P= Length of planned outage, months

= T_R = Length of refueling outage, months(in this report)

T_C= Length of refueling cycle, months

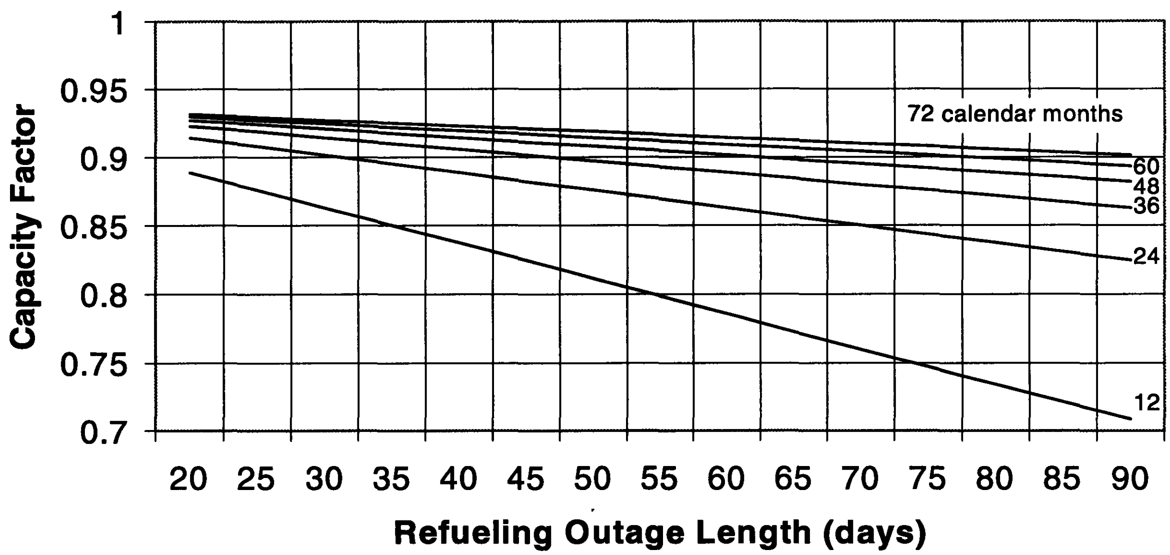
Hence, by increasing the time between refueling outages and shortening the time that these refueling outages take, nuclear plants can significantly improve their capacity factors. In this report, the effects of non-refueling planned outages on plant economics are not considered explicitly due to the wide variation in practice among plants; however, the analytic framework is set up to incorporate these effects on a plant specific basis. Thus, planned outage (T_p) time will be represented by refueling outage time (T_R) only in this report. Additionally, a decrease in the forced outage rate can further enhance the capacity factor. A more concrete illustration of how the improvement of these three factors will increase capacity factor can be seen in Figures 1-1 and 1-2.

Figure 1-1: Capacity Factor as a Function of Cycle Length for a Varying Forced Outage Rate and Fixed Refueling Outage Length (@30 days)



Optimizing these three variables in the interest of achieving the best possible capacity factor is the central focus of the extended cycle project at M.I.T., of which this work is part. By increasing the capacity factor, utilities can produce more electricity at comparable or reduced operating costs, yielding lower energy costs to the consumer. These lower costs are vital to the future of the nuclear power industry if it is to remain an economically feasible alternative to fossil fuel plants.

Figure 1-2: Capacity Factor as a Function of Refueling Outage Length and Cycle Length at a Constant Forced Outage Rate (6%)



However, since current fuel management practices, which for PWR units typically involve 3 batch, 18 month cycles and for BWR units typically involve 3 batch, 24 month cycles, are near the optimum based only on fuel cycle costs, extending cycle length will increase fuel costs. Hence, there is a tradeoff between plant Operational and Maintenance (O&M) savings and fuel cost increases that must be examined to determine whether a net economic benefit results. The economic evaluation of this trade-off is the central focus of this report.

Cycle lengths up to 48 and 75 calendar months will be examined for the BWR and the PWR, respectively, in this economic analysis, since this is the point at which batch-loaded cores exceed current NRC-mandated burnup limits. However, a more realistic target of 48 calendar months has been used for the core design and surveillance strategy that have been developed in conjunction with this project in order to confirm the technical feasibility of cycle length extension [M1, M2].

1.2 Background

Given that the primary motivation for investigating this new approach to plant operations is economics, determining how much of an improvement the extended cycle will make economically is paramount. Previous economic studies in this area by Ayoub and Li provide an excellent base from which to start this investigation [A1,L1]. Their reviews indicate that virtually all major costs and savings in implementing the extended cycle strategy in current reactors can be broken down into two categories: fuel cycle and operations and maintenance (O&M).

Preliminary analysis of the costs and savings associated with these two areas indicates that the fuel cycle considerations will incur significant costs, with opportunities for few savings. Primary among these costs are the increases in the fuel production expenses which result from the increased fuel enrichment necessary to sustain extended cycle lengths. The extended cycle core designs require core-average enrichments of ~4.9 $^{w}/_{o}$ U-235 for a 45.0 Effective Full Power Month (EFPM) core for the case study BWR and ~6.5 $^{w}/_{o}$ U-235 for a 38.8 EFPM core for the case study PWR as compared to the values of ~4.1 $^{w}/_{o}$ U-235 and ~4.4 $^{w}/_{o}$ U-235 used in current practice for these plants. This increased enrichment also leads to other expenses, including heavy burnable poison loading to control the increased reactivity, licensing, transportation, and back-fit of current processing facilities, all of which must be absorbed by utilities in the cost of the reactor fuel.

In order for extended cycles to meet the desired goal of economic attractiveness, these increased costs must be offset by significant savings in the operations and maintenance areas.

Fortunately, it is implicit in the purpose of this project both to decrease the frequency of refueling shutdowns and to limit the number of days of forced outage. A closer examination of surveillance strategies has also been made not only to insure that extended operating periods can be made consistent with necessary surveillance schedules, but also to improve the reliability and availability of plant components [M1]. The key to the economic viability of extended operating cycles is the successful development and implementation of these O&M savings factors.

TABLE 1-1: Definition of Case Study Plants and Base Cases

	BWR Reference Cycle	BWR Extended Cycle	PWR Reference Cycle	PWR Extended Cycle
Case Study Plant				
Plant Type	General Electric BWR 4/5		Westinghouse 4-loop	
Rated Specific Power (kW/kg U)	24.5		38.7	
Number of type in US fleet/ Total number B/PWRs	14/37		27/72	
Operating Parameters				
Cycle Length (months)	24	47.8	18	41.4
Batch Index Number (n)	3	1	2.68	1
Refueling Outage Length (days)	49	42	49	42
Forced Outage Rate (%)	6	3	6	3
Resulting Capacity Factor (%)	87.7	94.2	85.6	93.8

Using the parameters outlined in Appendix D and shown in Table 1-1, cases have been established for both a representative reference and extended cycle in the case study plants. The case study plants were chosen based on their relatively high specific power, which would undoubtedly prove most challenging in neutronic and fuel design, and because they are the largest type classes in the US utility fleet. The operating parameters selected for the reference cycle are consistent with current industry practice, while those determined for the extended cycle are best estimates for values likely to be achievable at the time of implementation of cycle length extension.

Both the complexity of the cost model compiled to determine LWR economics in this report and the variability of the factors within this model with cycle length suggest that the relationship between cycle length and economic benefit may not be direct. Therefore, a determination of the optimum conditions at which to operate, i.e. cycle length, FOR, RFO, n, would be beneficial.

1.3 Organization of this report

In this report, fuel cycle cost considerations will be explored in detail, while O&M factors will be handled more generally. This approach has been taken for two reasons. First, extended cycle cores have already been designed for both the PWR and BWR extended cycle cases and accurate predictions for core design parameters, i.e. core average enrichment, can be made for intermediate cycle lengths. Thus, most of the individual factors that determine fuel costs can be identified and reasonably quantified [M2]. Second, O&M savings are more complex in their dynamic and interdependent nature and it will require more effort to quantify them to the same level of confidence as fuel cycle costs.

In Chapter 2 of this report, the costs associated with implementing the new fuel cycle strategy will be examined. This analysis will be both qualitative and quantitative with costs compared to consistently calculated values for current fuel management practices.

The economic factors of O&M will be examined in Chapter 3. Where possible, estimates obtained from industry experts will be made of the actual dollar value associated with each factor. Research conducted by other members of the extended cycle group will also be used to help quantify some of the larger O&M factors.

Having identified all of the costs and benefits associated with extending operating cycles, a study can be performed to find the optimal cycle length extension between current practice and technical feasibility. This is the focus of Chapter 4.

Furthermore, because future costs of materials and services are uncertain, parametric studies will be performed to identify which factors have the greatest impact and thus which could be improved to help further reduce costs. This work will be done throughout Chapters 2 and 4 and will make use of graphs to visually demonstrate the effects of varying different parameters.

Finally, after looking separately at all of the factors involved, a comprehensive economic evaluation will be made. This will be done in Chapter 5 and will include suggestions for areas of further study to aid in the confirmation of the identified optimum cycle length.

1.4 Definition of terms

The various economic analyses performed in this work are based on the plant performance criteria of capacity factor. This and other important related terms used throughout this work are defined as follows:

Availability [L'] - the ratio of the actual electrical energy produced to the amount of electrical energy which could have been produced by operating the plant at 100% rated power *during non-planned outage time.*

Batch Fraction - the ratio of the number of assemblies replaced per refueling to the number of total assemblies in the core.

Batch Index Number [n] - the ratio of the number of total assemblies in the core to the number of assemblies replaced per refueling; the inverse of the batch fraction.

Base Cases - a generic reference to the scenarios used for comparing different operational practices for the case study plants throughout this report; the four base cases are outlined in Table 1-1, Appendix D and are labeled as the BWR reference cycle, the BWR extended cycle, the PWR reference cycle, and the PWR extended cycle.

Capacity Factor [L] - the ratio of the actual electrical energy produced to the amount of electrical energy which could have been produced by operating the plant at 100% rated power over a given time period. It is a function of availability, refueling outage length, and cycle length.

Case Study Plant - a generic reference to the type of BWR and PWR that is being analyzed in this report; the General Electric 1100 MW_e BWR 4/5 is the "case study BWR" and the Westinghouse 1150 MW_e 4-loop plant is the "case study PWR."

Core Load [M] – the mass of heavy metal uranium that is loaded into the core; nominal values of 138.7 MTU and 88.18 MTU are used for the case study BWR and PWR, respectively.

Core Specific Power [P] – the energy density of the reactor core expressed in units of kW_{th}/kg U; also known as full power burnup rate; nominal values of 24.5 kW_{th}/kg U and 38.7 kW_{th}/kg U are used for the case study BWR and PWR, respectively.

Cycle Length [T_C] - the length of time between similar time points, i.e. beginning or end, of refueling outages; measured in calendar months vice Effective Full Power Months (EFPM).

Forced Outage Rate (FOR) - 1 minus the availability.

Planned Outage Length [T_P] - the length of time that the plant shuts down for a planned outage to conduct any non-emergent work or maintenance; this includes refueling of the core and it associated tasks; equal to the refueling outage length (T_R) for the purposes of this report, given the wide variability in planned maintenance outage practice throughout the US fleet.

Rated Capacity [Q] - the designed maximum thermal power rating of the system; 3380 MW_{th} for the case study BWR and 3411 MW_{th} for the case study BWR; Q=MP.

Refueling Outage Length [T_R] - the length of time that the plant shuts down to perform refueling of the core and its associated tasks.

Unit Capability Factor - the percentage of maximum energy generation that a plant is capable of supplying to the electrical grid, limited only by factors *within the control of plant management*, i.e. length of planned and refueling outages. A high unit capability factor indicates effective plant programs and practices to minimize unplanned energy losses and to optimize planned outages. [I1]. This is a plant performance criterion used by the Institute for Nuclear Power Operations (INPO) and the World Association of Nuclear Operators (WANO).

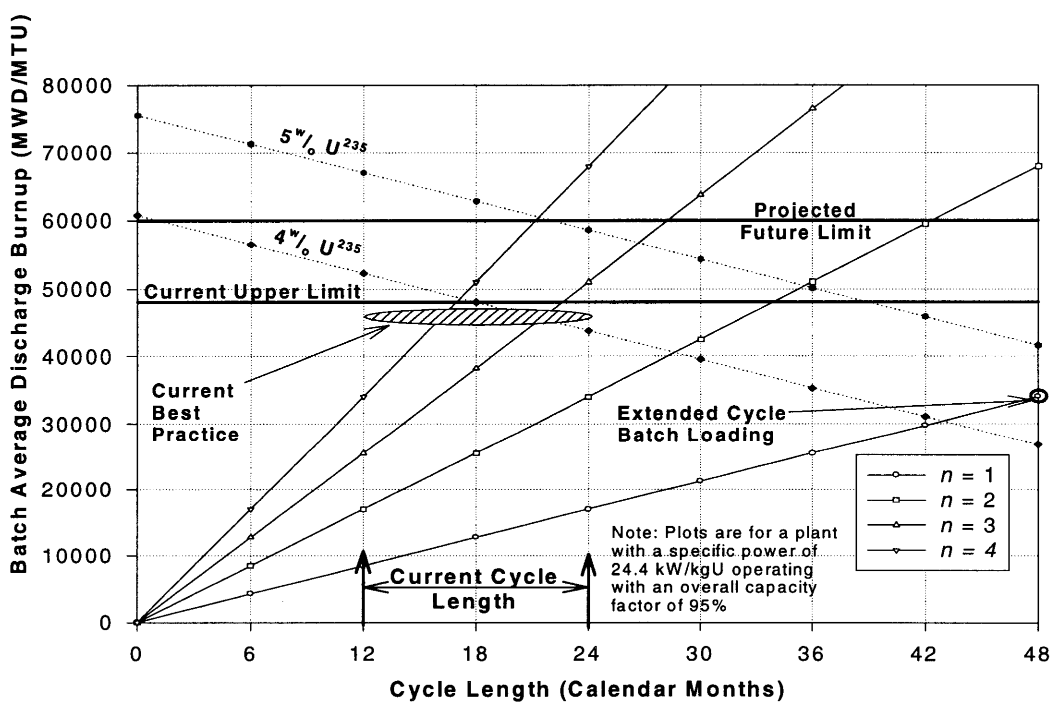
CHAPTER 2: FUEL CYCLE ECONOMIC FACTORS

2.1 Introduction

Of the three factors discussed in the introduction, only one, extension of the fuel cycle length, significantly affects fuel cycle economics. Refueling outage length, i.e. planned outage time) and forced outage rate are both primarily operational considerations and will be explored in the next chapter.

To determine what cycle length can be achieved, the relationships between discharge burnup and cycle length for both the case study BWR and PWR, shown in Figures 2-1 and 2-2, are informative.[1]

Figure 2-1:Burnup-Cycle Length Map for the Case Study BWR



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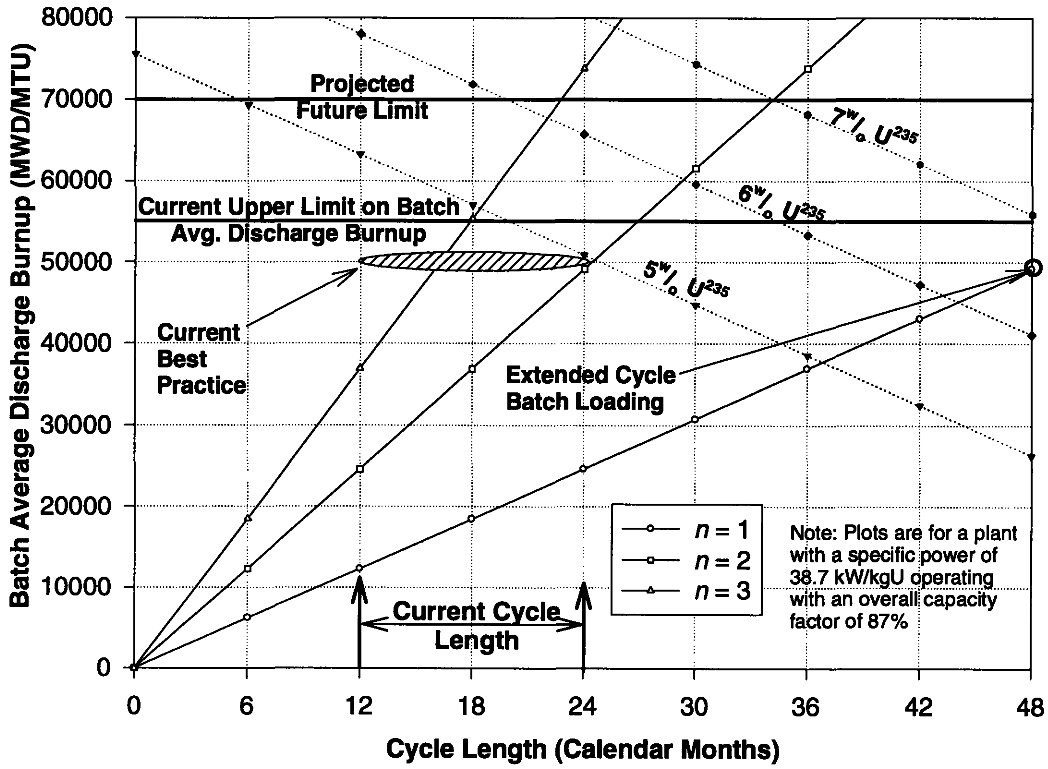
[1] Figures 2-1 and 2-2 represent results that were generated at the beginning of this research effort to act as an aid for predicting a target ultra-long cycle length. They are not associated with any of the operational parameters used to define the base cases and only serve to show some generic relationships between burnup, enrichment, cycle length, and batch index number.

Figure 2-2: Burnup-Cycle Length Map for the Case Study PWR



Plotted for different batch index numbers, n, this relationship shows that for a smaller n, the slope of the burnup line is less. For a batch index number of 1, cycle length can be maximized while still staying within current burnup limits set by the NRC and vendor warranties. Thus, from these figures, it can be estimated that the maximum realizable cycle length is 66 calendar months and 48 calendar months for the BWR and PWR, respectively. These estimates are made to the nearest six month increment, accounting for the nuclear utility practice of scheduling refueling outages (RFOs) in the fall or spring to avoid shutting down when electricity demand is highest in the summer and winter. Note that while the slope of the lines in Figures 2-1 and 2-2 will change as the operating parameters of the cycle change, i.e. RFO length, forced outage rate (FOR), and capacity factor, it serves to show that a batch index number of 1 and a higher enrichment are necessary for maximizing cycle length.

While the maximum technically feasible, i.e. burnup limited, cycle length was sought for both the BWR and PWR extended cycle cores, the design process showed that many technical limits other than the burnup constraint were challenged at this point. Consequently, overall economic optimization led to selection of a 48 calendar month cycle for the BWR extended cycle core design. In the case of the PWR, cycle length was shortened in order to achieve technical feasibility at ~41.4 calendar months (38.8 EFPM at a 93.8% capacity factor).

As a result of increasing the cycle length to 48 and 41.4 calendar months, and decreasing the batch number index to 1, it is necessary to increase the enrichment of the fuel in order to sustain criticality throughout the life of the core. Specifically, this requires enrichments as high as 7.4 $^{w}/_{o}$ for the BWR and 7.0 $^{w}/_{o}$ for the PWR, yielding core average enrichments of ~4.9 $^{w}/_{o}$ and 6.5 $^{w}/_{o}$, respectively. Because of this increased enrichment, it is also necessary to increase the amount of burnable (BWR, PWR) and soluble (PWR) poisons in the core to control criticality throughout the cycle. Although both changes represent increased expenditures, the costs associated with an increase in the enrichment of the fuel are far more significant and appear to be the largest economic hurdle to implementing an extended refueling cycle.

In this chapter, the fuel cycle economic factors will be considered under four categories: realizable costs, potential costs, realizable savings, and potential savings. This distinction is necessary so that it is clear which factors will have an immediate effect and which factors have the potential to have an impact on fuel cycle economics due to technological innovation and changing policy and operational procedures.

In what follows, the proposed single batch extended cycle BWR and PWR core designs are compared to current practice. The base case parameters are documented in both Table 1-1 and Appendix D. The economic analysis uses a simple but adequately accurate approach discussed in Reference [A1] and summarized in Appendix B. The reference case economic parameters, also tabulated in Appendix D, are taken from Reference [O1].

2.2 Realizable costs

2.2.1 Front end costs

Within the fuel cycle, the part which is obviously most quantifiable is the front end. This is due in large part to the availability of competitive commercial pricing information from industry on the goods and services required to supply reload fuel to LWRs. As well as being the best defined, the front end of the fuel cycle also represents the largest single realizable cost in implementing the extended fuel cycle strategy.

The front end of the fuel cycle involves four major steps: mining, conversion, enrichment, and fabrication (transportation between these cost centers is a small increment and is included in the costs quoted in the present analysis). Each of these aspects will be analyzed both qualitatively and quantitatively in an effort to better understand how the increased enrichment of the fuel will impact fuel cycle costs. A flow chart outlining the front end of the fuel cycle and how the various mass flow rates of uranium product necessary for each step are calculated can be found in Appendix A.

2.2.1.1 Mining

Since the enrichment of uranium remains constant during the mining process (0.711 $^{w}/_{o}$ U^{235}) from the actual mining to the delivery of the U_3O_8 or "yellow cake" to the conversion plant, the only effect that increased fuel enrichment has on this part of the front end fuel process is the increase in the amount of uranium fed into the enrichment process to achieve a higher enriched product ready for fabrication. As this mass flow rate is increased, and the unit cost for natural uranium remains constant, the cost of the fuel due to mining considerations will also increase for an extended cycle core. Table 2-1 illustrates the discounted unit fuel cost per processing step and shows the increase for the mining step to be only ~10% for the BWR and as great as ~50% for the PWR. This large disparity in cost increase for the two case study plants is due to the difference in the enrichment increases from the reference to the extended cycle core design.

Table 2-1: Fuel Cost Comparison for an Extended Operating Cycle

	Extended Cycle BWR	Reference Cycle BWR	Extended Cycle PWR	Reference Cycle PWR
Core Average Enrichment ($^{w}/_{o}$ U-235)	4.9	4.1	6.5	4.4
Mining ($/kg)	719	642	943	637
Conversion ($/kg)	110	99	144	98
Enrichment ($/kg)	1108	942	1568	953
Fabrication[2] ($/kg)	349	384	361	370
Subtotal ($/kg)	**2286**	**2067**	**3016**	**2058**
Government Waste Disposal Fee ($/kg)	267	254	382	270
TOTAL ($/kg)	**2553**	**2321**	**3398**	**2328**
Core Load (MTHMU)	135.504	138.7	85.3975	88.18
Cost of Core ($M)	345.5	321.9	290.2	205.3
A: Annual Fuel Cost ($M/yr.)	**86.7**	**53.6**	**84.0**	**51.1**

2.2.1.2 Conversion

Similar to the mining step, the conversion from U_3O_8 to the UF_6 necessary for the enrichment stage involves no change in enrichment. This means that the only change in the price

[2] Includes a weighted average cost for burnable absorbers.

of the fuel due to conversion is the larger amount of yellow cake converted to UF_6. This increased mass flow rate causes the cost component of fuel due to conversion to again change by about the same amount, ~10% for the BWR and ~50% for the PWR.

2.2.1.3 Enrichment

Since the costs associated with the entire front end of the nuclear fuel cycle are in one way or another dependent upon the enrichment of the fuel, an understanding of how increasing the enrichment of the fuel will increase fuel costs is crucial. Based on the Separative Work Units (SWU) required, the cost of enrichment depends upon the enrichment of the uranium being fed into the process, the enrichment of the uranium in the waste or "tails," and the enrichment of the uranium in the product; that is, the enrichment of the fuel (see Appendix A for the governing relation). Given that the only factor to change in this case is the enrichment of the fuel, we can calculate that for a ~0.8 $^w/_o$ (~20%) and ~2.1 $^w/_o$ (~50%) increase in core average enrichment, an increase of about 18% and 65% for the discounted cost of enrichment results. These results as well as other detailed calculations suggest a linearity of SWU costs over a short range of enrichments, which will be discussed later.

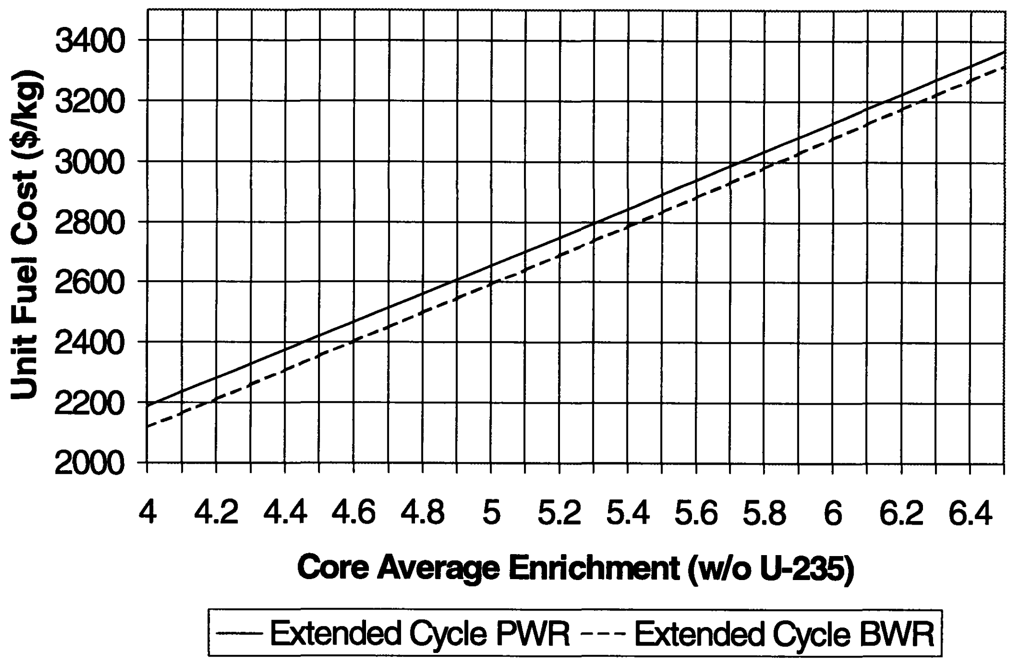
In addition to the increase in the number of SWU that must be bought to provide for the increased enrichment, other costs associated with enrichment may further drive up fuel costs. Because most current U. S. enrichment plants are only licensed to handle uranium up to 5 $^w/_o$, industry would be required to take steps to increase this limit. It is interesting to note that URENCO of the Netherlands has indicated that it has a current capability of producing up to 10 $^w/_o$ fuel, an aspect worthy of further investigation in helping determine the costs associated with modifying enrichment limits.

Increasing fuel processing enrichment limits would include performing criticality safety analyses on current enrichment plants to see if they could handle the change. Should the plant be found not currently able to handle these limits, modifications would have to be made to the plant, incurring large capital costs. However, these costs may not be too significant if they were amortized over several utilities and several core reloads [M5].

Another factor that could play a significant part in costs due to enrichment is the cost of transportation of the enriched fuel to the fabrication facility. Already included here in the cost of SWU, transportation means are only licensed for 5 $^w/_o$ and may require modification to safely handle an enrichment increase. As with the concerns for increasing licensed limits for the enrichment facility, the associated transportation would also need criticality safety analyses, licensing studies, and back-fit, if necessary. While any cost increase associated with increasing enrichment limits for transportation would more than likely be passed on to the consumer, this cost increase may be marginal if shared by several utilities for several core reloads, as is predicted for the capital costs associated with such a change.

Since enrichment is the key factor in determining front-end fuel cycle costs, a parametric study was performed which looked at the cost of fuel as a function of enrichment. Although the relationship between enrichment and SWU is not quite linear, if this analysis is performed over a small range of enrichments, an excellent linear approximation between enrichment and direct (i.e. undiscounted) fuel cost results, as shown in Figure 2-3. If core average enrichment could be reduced by 0.5 $^w/_o$, a savings of about \$236/kg and \$241/kg or about \$8M/yr. and \$6M/yr.could be realized in fuel costs for the extended cycle BWR and PWR, respectively (assuming a negligible change in cycle length). Thus, the possibility of optimizing the core to decrease enrichment, i.e. use of reflector pins in the peripheral assemblies, makes an extended cycle more attractive. This linearity of fuel costs with respect to enrichment also simplifies the core cost calculation since it allows core costs to be calculated based only on this core average enrichment and the core loading, avoiding the complexity associated with the heterogeneity of the extended cycle core designs.

Figure 2-3: Economic Effect of Enrichment



2.2.1.4 Fabrication

Representing the smallest portion of the front-end fuel cycle costs, fabrication costs actually decrease for an extended cycle. This is primarily due to the decreased carrying charges caused by the decreased time to the midpoint of irradiation. While it appears that this decrease is only a slight one, it does not take into account several factors. First, the unit cost for fabrication in this table is taken from an IAEA study based on 1991 prices [O1]. This price is for the enrichment used in 18 calendar month cycle plants and does not take into account the criticality safety analyses, licensing studies, and possible back-fit that will have to be performed on the fabrication plant in order to increase the level of enrichment it can handle.

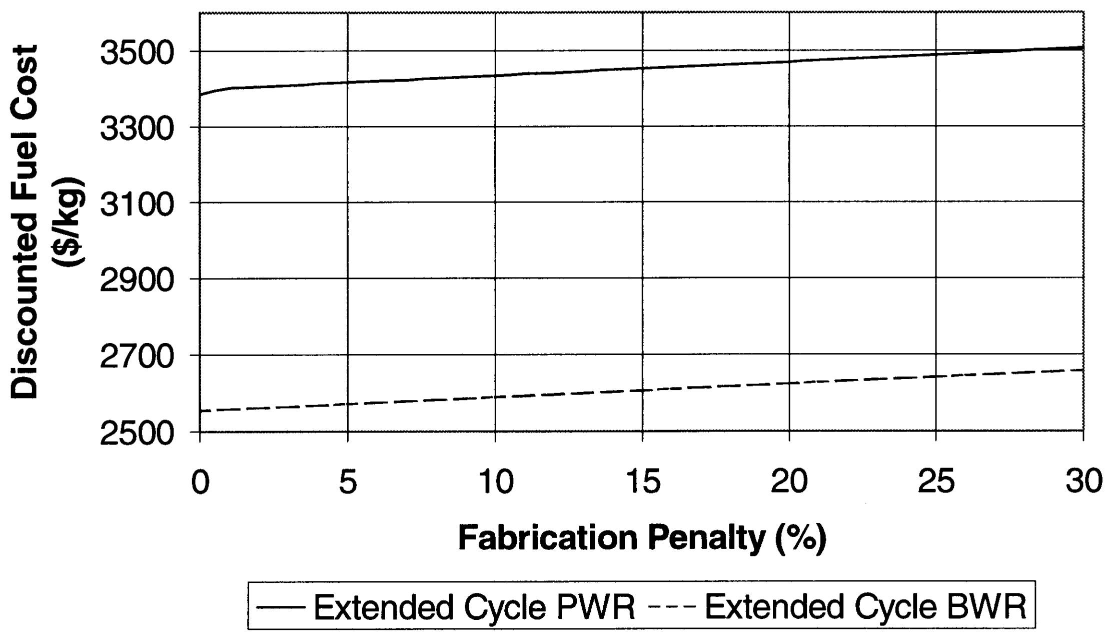
Another factor that needs to be taken into account is the increase in the burnable poison in the fuel. Advantageous with respect to transportation costs for this part of the fuel cycle, the heavily-poisoned extended cycle fuel is so heavily poisoned after fabrication that it will have less reactivity than current 18 calendar month cycle fuel, eliminating the need for modification to transportation infrastructure for these assemblies. This is only an advantage, however, if regulations governing transportation of nuclear fuel can be modified to allow reactivity credit to be taken for burnable absorbers. However, less heavily poisoned assemblies, i.e. those with 24 burnable absorber pins or less for the extended cycle PWR, have more reactivity than assemblies used in current practice and may consequently require a restructuring of part of the transportation infrastructure.

The increase in burnable poison loading, however, does create another problem. To manufacture a fuel pellet containing integral Gd_2O_3 (gadolinia) as a burnable poison, UO_2 and Gd_2O_3 powders are combined and cold pressed into a "green" pellet having a density ~60% of the theoretical density. These pellets are then loaded onto molybdenum "boats" and baked in a high temperature sintering furnace until their densities are increased to ~96% of theoretical. These furnaces must be maintained with a reducing atmosphere during the sintering process, limiting the number of high oxygen-to-metal-ratio pellets that can be baked in a given batch. For pellets containing high concentrations of Gd_2O_3 (as in the 12 $^w/_o$ and 10 $^w/_o$ concentrations that are used in the BWR and PWR extended cycle core designs) only half as many can be baked simultaneously (compared to UO_2-only fuel), due to excess oxygen liberated in the sintering process. This can, therefore double the cost of this step in fabrication of the poison pellets. Since only 2300 out of 69,524 and 5772 out of 50952 fuel pins, or about 3% and 11% of the BWR and PWR core are poisoned, fabrication costs due to this factor can be hypothesized to increase by the same percentage. Looking at the parametric study conducted to determine the effect of fabrication penalty on fuel costs shown in Figure 2-4, this 3% and 11% equates to an increase of \$10.5/kg fuel and \$51.7/kg fuel or ~\$0.4M/yr. and ~\$1.3M/yr. This cost is not included in later analyses, as it is somewhat speculative and sufficiently small to be ignored in a scoping study.

Another potential fabrication cost penalty that must be considered is the use of the exotic burnable poison combination proposed in the PWR core design. Using a combination of gadolinia and IFBA (Integral Fuel Burnable Absorber), this design combines burnable poisons which different vendors currently manufacture exclusively. Either a cooperative effort must be undertaken between competing fuel vendors or a single vendor will have to expand their burnable poison production options in order for such a fuel design to be feasible. Whichever option is chosen, it will more than likely lead to an increase in the unit cost of fabrication. While it would be too speculative to try to quantify, the penalty itself is a reality and must be considered, since the PWR core design relies on this unique combination of burnable absorbers for technical feasibility.

Given that the fuel assemblies will operate at or above core-average power for a longer time in the extended cycle core design, they will experience higher temperatures for a longer time than in an 18 calendar month cycle core. These prolonged, elevated temperatures will most likely increase the effects of waterside corrosion on the fuel assemblies. As a result, the cladding may

Figure 2-4: Discounted Fuel Cost as a Function of Fabrication Penalty



have to be upgraded. A promising prospect to mitigate this corrosion is Westinghouse's Zirlo®, which would increase fuel costs by a total of $1-2M per full core, as estimated by an industry expert [G3]. Siemens also markets a duplex cladding which addresses the same problem. Corrosion studies using state-of-the-art computer models will be performed in the near future to help resolve this issue. In any event, $2M/core or $0.5M/year is a small penalty compared to the other cost increments involved. This figure is not included in later analyses as it is hypothesized that all plants, regardless of cycle length or batch number index, will use premium cladding by the time that an extended cycle strategy is implemented. This also assumes that the cost of the premium cladding will be passed along to utilities in the form of higher unit fabrication costs, whose effect can be assessed from Figure 2-4.

2.2.1.5 Fuel handling concerns

As mentioned previously, uranium handling during the front end of the fuel cycle would raise reactivity limit concerns during transportation between the enrichment and fabrication stages. Another factor that needs to be explored is that the number of assemblies transported per core reload between all stages in the front end of the process will increase almost three-fold with a 48 calendar month cycle strategy. This raises questions about whether the logistical capability of fuel manufacturers, shippers, and at-reactor staff would have to be expanded, driving up the unit costs of fuel processes, or, if lead times would need to be increased, translating into larger carrying charges. This logistical capability includes not only transportation costs, but also encompasses factors such as increasing manpower for handling and inspection of the fuel assemblies. Further, since the number of assemblies handled in a short period of time increases, modifications may need to be made to existing storage and handling facilities.

2.2.2 Back end costs

Currently, no permanent solution has been put into operation to dispose of High Level Waste (HLW) from nuclear power plants. Some temporary at-plant solutions are available: augmented spent fuel pools and the addition of dry storage to hold the fuel discharged from the reactor. With the implementation of an extended cycle refueling strategy, new consideration must be given to what will happen at the back end of the nuclear fuel cycle. In particular, the spent fuel is more reactive, as shown in the following analysis.

2.2.2.1 Storage and disposal

2.2.2.1.1 Reactivity of spent fuel

Since the fuel that will be used for an extended cycle core is at a higher enrichment and will not achieve higher burnup than conventional multi-batch fuel, the reactivity of the spent fuel will increase. In fact, the spent core is critical at hot full power, hence supercritical at cold zero power in the absence of added poison. This can be shown in what follows:

Given the relationship between reactivity and batch average discharge burnup (for unpoisoned fuel) [D1]:

$$\rho\,(B_d) = \rho_o - A^{*}B_d \qquad \{2\text{-}1\}$$

where: $\rho\,(B_d)$ = reactivity as a function of discharge burnup

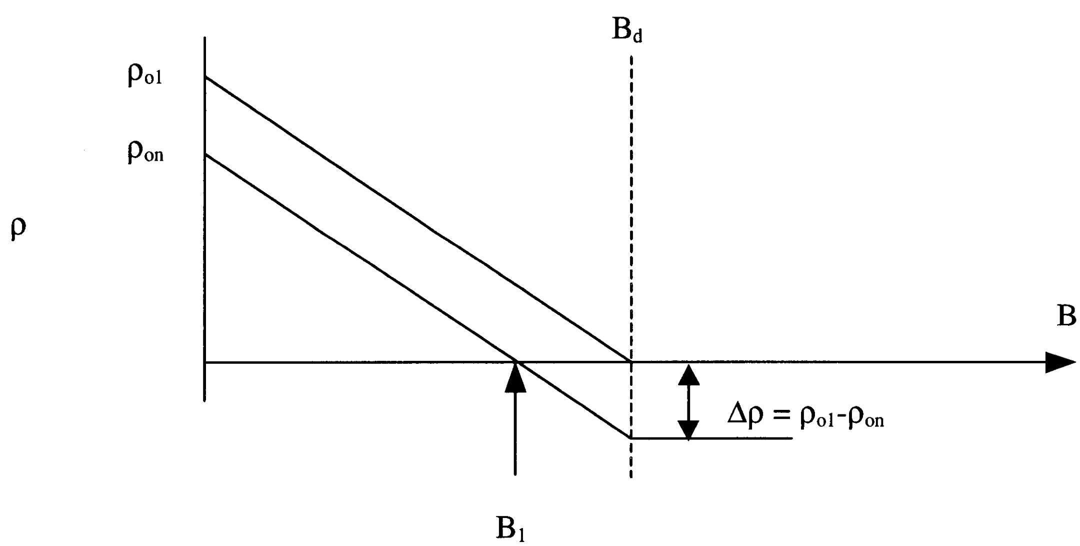
ρ_o = initial reactivity

A = slope constant in linear $\rho\,(B_d)$ approximation, kg/MWD

B_d = batch average discharge burnup, MWD/kg

We can show this relationship graphically for both a 1 batch and n batch case having the same batch average discharge burnup:

Figure 2-5: Linear Reactivity Comparison of a Batch Loaded and n-Batch Core



Given also the relationship between batch average discharge burnup, B_d, batch index number, n, and the batch-loaded burnup capability, i.e. burnup for an n=1 core when ρ=0, [D1]:

$$B_d = \left(\frac{2n}{n+1}\right) B_1 \qquad \{2\text{-}2\}$$

where: B_d = batch average discharge burnup, MWD/MTU

n = batch number index (1/n th of the core replaced each refueling)

B_1 = batch-loaded burnup capability, MWD/MTU

Assuming the same slope, A, for both cases, similar triangles exist in the graphical representation and thus:

$$\frac{\rho_{o1}}{\rho_{on}} = \frac{B_d}{B_1} = \left(\frac{2n}{n+1}\right) \qquad \{2\text{-}3\}$$

Therefore:

$$\Delta\rho = \rho_{on}\left[\frac{n-1}{n+1}\right] \qquad \{2\text{-}4\}$$

$$\Delta\rho = \rho_{o1} - \rho_{on} = \rho_{on}\left[\frac{2n}{n+1} - 1\right] \qquad \{2\text{-}5\}$$

where: $\Delta\rho$ = extra spent fuel reactivity of a 1 batch cycle fuel as compared to an n-batch conventional fuel cycle having the same B_d.

Thus, for n=3 and n=2.68 (as in the BWR and PWR reference cycles, respectively):

$$\Delta\rho_{BWR} = \rho_{o3}\left(\frac{1}{2}\right) \approx 0.11 \text{ for a typical case}$$

$$\Delta\rho_{PWR} = \rho_{o2.68}\left(\frac{1.68}{3.68}\right) \approx 0.10 \text{ for a typical case}$$

Hence, there will be a significant increase in the reactivity of the spent fuel for the 1 batch case as compared to current practice. This may cause problems in current temporary waste storage facilities since they are designed around spent fuel reactivity limits associated with 24 and

18 calendar month cycles. Consequently, a criticality safety analysis would need to be done on existing facilities to determine if modifications need to be made. If so, then costs will be incurred for the engineering, licensing, and construction necessary to modify existing facilities or to build a new facility. The most effective solution may be to purchase poison inserts for the spent fuel pool, such as those currently being marketed by Framatome and Siemens. Additionally, the same cost concerns apply to the transportation necessary to get the spent fuel from its temporary to its permanent disposal site. Fortunately, the government is responsible for all of these transportation costs, which will be covered by the federally imposed 1 mill/kwhre surcharge on nuclear generated electricity. However, the limits on the reactivity of the spent fuel that the government will ship have yet to be defined and it is hypothesized that a premium may be charged for fuel that is beyond these limits. Regardless of the reactivity concerns involving spent fuel or the magnitude of cycle length extension, the capacity for temporarily holding spent fuel will need to increase for all core management options as a permanent disposal facility will not be available for at least 14 years and temporary sites are filling rapidly.

2.2.2.1.2 Volume of spent fuel

An important factor to consider when discussing disposal is the effect on the volume of spent fuel that will be generated due to an extended operating cycle. Generically, the annual number of spent fuel assemblies produced from a nuclear power plant, a, can be expressed as:

$$a = \frac{A}{\left(\frac{n * T_C}{12}\right)} \qquad \{2\text{-}6\}$$

where: a = annual number of spent fuel assemblies produced in a plant, assemblies per year

A = total number of assemblies in core

n = batch index number

T_C = cycle length, calendar months

Figure 2-6: Annual Generation of Spent Nuclear Fuel for Extended Operating Cycles in the Case Study BWR

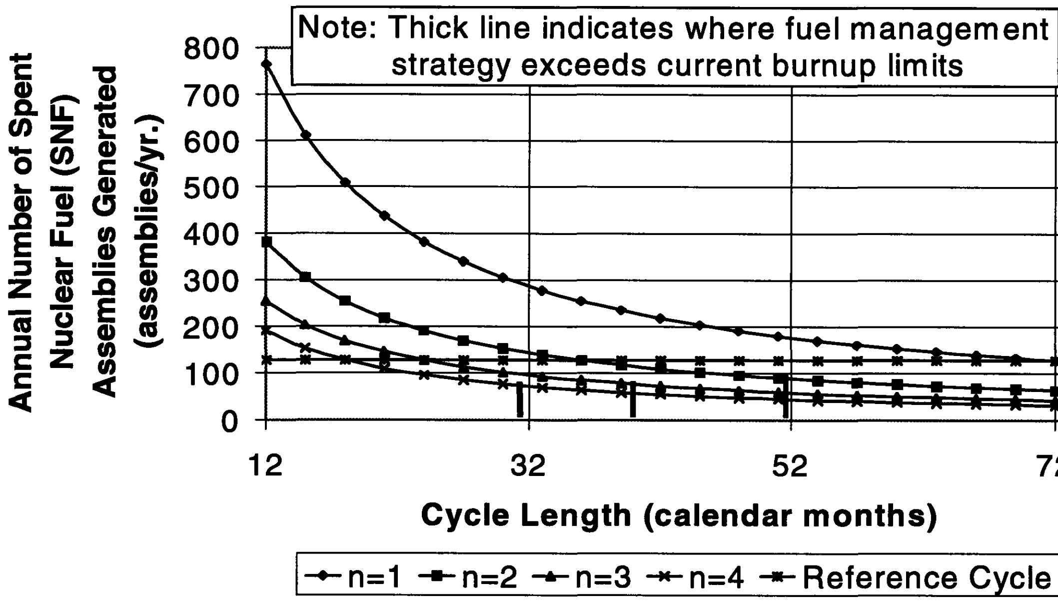
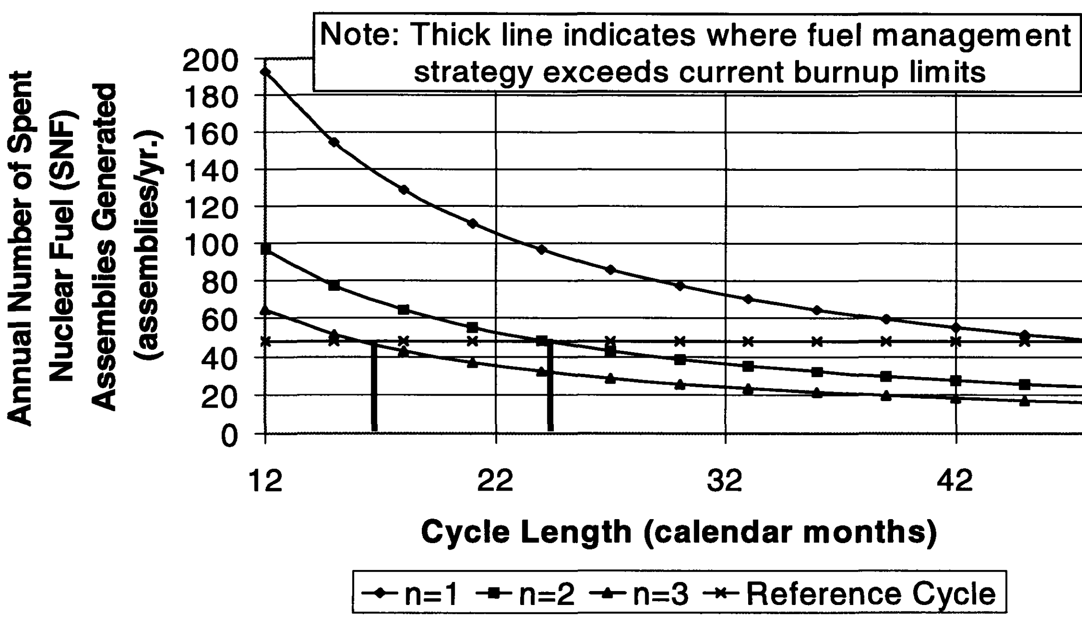


Figure 2-7: Annual Generation of Spent Nuclear Fuel for Extended Operating Cycles in the Case Study PWR



Applying the respective operating parameters of the reference and extended cycle cases to Equation {2-6}, the annual number of spent fuel assemblies generated by using a batch loaded extended cycle strategy would increase from 128 to 192 (50% increase) and 48 to 56 (17% increase) for the case study BWR and PWR, respectively. The relationship between the amount of spent fuel that is generated annually, cycle length, and batch index number is shown in Figures 2-6 and 2-7 for the case study BWR and PWR.

Given that most utilities are at or near their capacity with their spent fuel pools, the increased generation of spent nuclear fuel (SNF) associated with batch-loaded extended operating cycles will cause nuclear utilities to incur an additional cost to implement a temporary storage solution, i.e. dry cask storage, until the fuel can be taken away by the Department of Energy. This cost can be quantified simply by:

$$B=(a_{ext}-a_{ref})*d \qquad \{2\text{-}7\}$$

where: B = cost increase from an increased volume of spent fuel, \$M/yr.

a_{ext} = number of spent fuel assemblies generated per year for an extended cycle, assemblies per year

a_{ref} = number of spent fuel assemblies generated per year for a reference cycle, assemblies per year

d = unit cost of dry cask storage, \$M/assembly

Additionally, since reimbursement for this temporary solution is in question and utilities are currently bearing this cost, utilities are storing their extra SNF in the cheapest of three options, single purpose cannisters. The unit cost, d, of these facilities is estimated at \$0.012M/assembly and

$0.02M/assembly for BWRs and PWRs respectively, yielding the cost increase shown in Table 2-2 [G1].

Although these cost increases are small compared to the significant fuel cost increases associated with extended operating cycles, the increased volume of spent fuel presents a large barrier to implementation of operating cycles at these ultra-long lengths, given the current political and industry emphasis on spent fuel and waste minimization. However, as cycle lengths get longer and batch index numbers increase, the annual spent fuel disposal rates of extended operating cycles decrease, shown in Figures 2-6 and 2-7. The economics associated with this factor will be explored further in Chapter 4.

Table 2-2: Comparison of Costs from the Storage of the Increased Volume of Spent Fuel

	BWR Reference Cycle	BWR Extended Cycle	PWR Reference Cycle	PWR Extended Cycle
Cycle Length (calendar months)	24	48	18	41.4
Amount of SNF generated, ass/yr.	128	192	48	56
Unit cost of SNF storage ($M/day)	0.012	0.012	0.02	0.02
B: Annual Cost of Storage ($M/yr.)	1.54	2.30	0.96	1.12
Cost Increase ($M/yr.)	0	0.76	0	0.16

2.2.2.1.3 Full core discharge for refueling

One must also investigate how refueling an entire core at one time will affect outage time and refueling operations. Currently, removing all fuel from the core during refueling as a means for decreasing the radiation exposure for plant personnel who must perform maintenance within containment is a preferred option. Most U. S. plants not only have the capability but also the experience and approval necessary to implement this strategy [E1]. Thus, this aspect of plant operations may not be a factor should an extended cycle strategy be implemented.

2.2.3 Transition cycle costs

2.2.3.1 Transition between the reference and extended cycles

Since the longest operating cycle to date that has been used is 24 calendar months, operating a nuclear reactor for ultra-long lengths will undoubtedly require many regulatory and operational changes [O2]. In order to change between the two modes, a transition period will be necessary. Aspects that will need to be examined and modified during this transition cycle include criticality safety analyses, licensing costs, and training and education of the plant workforce. The first two of these factors involve the utility incurring up-front costs, while the last factor is a cost that is spread out over the life of the plant.

2.2.3.1.1 Transition period

As adequate analysis has not yet been performed to determine what would be the best transition cycle strategy, a best versus worst economic case scenario will be employed for the purpose of this evaluation. The simplest and most costly transition strategy is to discharge the entire last n-batch core and replace it by a new extended cycle 1-batch core. In order to determine how much of the core has been burned, we must refer to Eq. {2-2} which demonstrates the relationship between end of cycle core average burnup, batch index number, and achievable discharge burnup [D1]:

$$\overline{B_c} = \left(\frac{n+1}{2n}\right) B_d \qquad \{2\text{-}8\}$$

where: $\overline{B_c}$ = end of cycle core-average burnup, MWD/kg

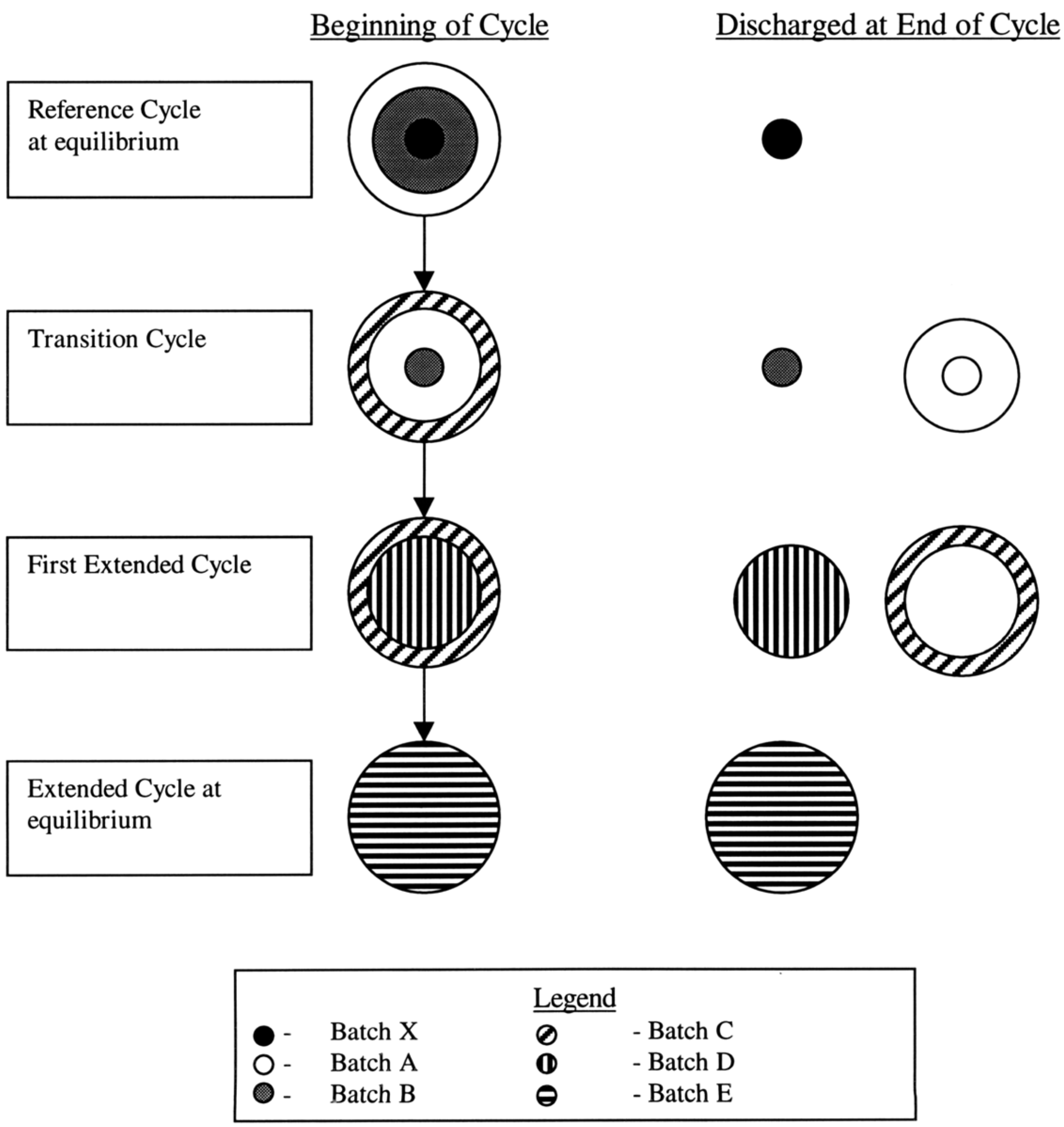
where: $\overline{B_c} = B_1$ for a batch-loaded core

n = batch index number

B_d = batch average discharge burnup, MWD/MTU

Thus, for a 3 or 2.68 batch strategy, only ~2/3 of full discharged fuel burn-up is achieved at the end of any cycle; hence, discharging this core leaves 1/3 of the energy unrecovered. For the 24 and 18 calendar month BWR and PWR reference cores upon which this analysis is based (138.7 MTHMU at $2321/kg and 88.18 at $2328/kg), this represents a loss of ~$107.3M and ~$68.4M. Levelizing this cost over the 20 year life of the extended cycle plant, losses of ~$12.4 M/yr. and ~$7.9M/yr. are realized (using continuous cashflow and continuous compounding at 10% - see Appendix B for details). As will be seen later, these are quite significant penalties.

Figure 2-8: Diagram of Best Case Transition Cycle Strategy



While a myriad of other transition cycle strategies can be envisioned, the best case scenario is one in which there is the smallest monetary loss, illustrated in Figure 2-8. This can be achieved by loading highly enriched, highly poisoned fuel in the outer 1/3 of the transition cycle core, (C, in Figure 2-8), leaving both a once and twice burned batch (A and B, each 1/3 of the core) in the interior from the previous reference cycle.

The outer part of the transition cycle (C) could then be rotated and re-used in the first extended cycle, with a fresh load used for the interior of the core (D). While one batch in the interior of the transition cycle core (A) will only be 2/3 fully burned at the end of the transition cycle (equating to a 1/9 loss in usage of fuel), the cost of this 1/9 can be made up if the outer part of the transition cycle is charged against the cost of the first extended cycle core and not the transition core. From the standpoint of the transition cycle, 1/3 of the core, (C), is being burned for 1/3 of its operating life, for free. Thus, re-using the periphery makes up for the cost of the fuel not economically burned from the 3-batch cycle. While 5/24 and 1/12 of the extended cycle core assemblies would be lost from the 1/3 of the fuel on the outer part of the transition cycle when it is employed as the 1/8 and 1/4 periphery part of the BWR and PWR extended cycle cores, this represents a small cost. Optimizing the enrichment loading patterns in the outer part of the transition cycle core to improve neutron economy would need to be employed to mitigate the costs of the 5/24 and 1/2 loss for the case study BWR and PWR, respectively.

Aside from the economic factors, there are some other concerns that come into play when determining what transition cycle strategy should be used. Since the longest operating cycle that has been run to date is 24 calendar months, a sequence of progressively longer cycles of greater length than this (e.g. 6-12 calendar month increments) may need to be run in order to convince appropriate regulatory authorities through demonstration and practice that operation at longer cycle lengths is safe. Additionally, a cycle length of intermediate length would help plant personnel make a better transition to an extended cycle as they would have more time to understand and embrace all of the operational changes. Hence, the utilities themselves may prefer a step-by-step approach. It is these concerns that will have to be better understood to determine the economic impact that the transition cycle will have on this project.

2.2.3.1.2 Implementing the extended cycle

Once the transition to the extended cycle core is made, the entire core will need to be replaced. The possibility of re-using peripheral assemblies from the transition cycle exists, depending upon the transition cycle scheme used. The next extended cycle reload would then be completely new fuel, as the peripherals would be twice burned (transition cycle plus first extended cycle) and the Radial Blanket Assembly (RBA - see section 2.4.1) strategy would be used for the periphery as it is the most advantageous. Either way, implementing the extended operating cycle will require at least one full batch extended cycle core reload.

2.2.3.2 End of reactor licensing life

One inherent advantage that the extended cycle presents is that at the end of the reactor licensing life, all of the fuel in the core is burned to its designed burnup. With a 3-batch cycle, there exists the penalty of still having 2/3 of the fuel which is not economically burned, representing a 1/3 fuel value loss.

2.2.4 Control rod replacement

Since a higher enrichment fuel will be used in the extended cycle, the neutron energy spectrum will be "hardened," or shifted toward higher energies, i.e. there will be a higher ratio of epithermal to thermal neutrons. This hardening of the spectrum results in a reduction in control rod worth. To counter this, some of the control rod absorber pins, currently B_4C and Ag-In-Cd for the BWR and the PWR, will need to be replaced with higher worth rods, such as those made with B_4C with 100% B^{10} enrichment and B_4C with natural B isotopic concentrations, respectively [M2]. These increased-worth control rods cost more than the rods currently in use, incurring a marginal cost increase for the extended operating cycle.

Since current BWRs replace 0-24 control rods every RFO (yielding a control rod lifetime of ~15 years) and PWRs replace their control rods every 15-20 years, control rod replacement would represent less of an expense if current cores were augmented with the extended cycle strategy at the same time that the control rods were scheduled to be replaced [T4]. However, the small amount of money (estimated at \$2.65M, or \$0.3M/yr. levelized over 20 years, for the PWR) that would be saved using this strategy is insignificant compared to other economic factors, and hence not important in determining when to implement an extended refueling cycle.

2.3 Potential costs

2.3.1 Reactor vessel fluence

In the single batch extended cycle core design, burnable poisons are used to produce a flat radial power profile. Consequently, if a highly enriched uniform core loading were used, more power would be produced in the peripheral assemblies of a typical extended cycle core than in the peripheral assemblies of low leakage cores currently in use. As a result of this increase in peripheral assembly power, the reactor pressure vessel (RPV) will experience an increase in the rate of neutron fluence accumulation. This higher fluence accumulation hastens the neutron embrittlement of the vessel, decreasing its toughness and shortening its effective life. While this is a problem because it can raise serious safety as well as economic issues, there are several ways to combat this problem. For example, the use of nickel reflector pins in the peripheral assemblies would reduce the fluence to more acceptable levels, but this could cause higher burnup and power peaking in the interior of the core.

Yet another way to handle the problem of increased fluence would be to accept this as part of normal reactor operations and conduct periodic repair or replacement of the reactor vessel when necessary. One such method of repair currently being explored is thermal annealing, a process which restores 80% of the ductility and fracture toughness of the vessel and extends the safe operating life of the vessel for many years. This solution would not only incur material and manpower costs ($6M for the first U. S. test in July 1996), but also takes a significant amount of time to perform (2 weeks), meaning more down time and less revenue. [A2]

Fortunately, there is a solution to this problem. With use of specially designed radial blanket assemblies (RBA) on the periphery, the reactor vessel fluence will be less than that of current low-leakage core designs [M2]. As discussed in the next section, this RBA strategy could even realize a savings with respect to degradation of the vessel when implemented in LWRs. However, no credit will be taken for this possibility of enhancing vessel lifetime.

2.4 Realizable savings

2.4.1 Radial blanket assembly (RBA)

In order to maximize the economic benefit for extending cycle length while reducing fluence on the reactor vessel, the RBA strategy will be implemented in the periphery of the extended cycle core design (see Ref. [M2] for details). Using 10% annular fuel pins at 7 $^{w}/_{o}$ enrichment in the inner 13 pins (with a 5.25 $^{w}/_{o}$ axial blanket) and unenriched (0.711 $^{w}/_{o}$) non-annular fuel in the outer 4 pins of the peripheral assemblies, the RBA strategy applied to an extended cycle PWR represents significant savings at the front end of the fuel cycle, as shown in Table 2-3.

Similarly, the BWR extended cycle core design uses 3 different radial enrichment zones and 5 different axial zones for its RBAs with enrichments at 0.711 $^{w}/_{o}$(natural), 1.00 $^{w}/_{o}$, 1.25 $^{w}/_{o}$, 1.27 $^{w}/_{o}$, 1.50 $^{w}/_{o}$ to achieve fuel cost savings. Since Reactor Pressure Vessel (RPV) neutron embrittlement is much less of a concern in a BWR than it is in a PWR because of its annulus of recirculating water and downward flowing feedwater between the core and RPV, the BWR RBAs can tolerate higher enrichments on the extreme periphery of the core than the PWR RBAs. The more optimum level of enrichment found in BWR RBAs allows for a longer cycle lengths while maintaining an acceptable level of neutron economy.

TABLE 2-3: Fuel Cost Savings Realized by Using the RBA Fueling Strategy

	BWR Extended Cycle w/out RBAs	BWR Extended Cycle w/RBAs	PWR Extended Cycle w/out RBAs	PWR Extended Cycle w/RBAs
Peripheral Assembly Average Enrichment (w/o U-235)	5.9	1.29	7	5.4
Cost per Peripheral Assembly ($M.)	0.56	0.17	1.47	1.21
Number of Peripheral Assemblies	92	92	44	44
Savings Over Core Life($M)	0	35.9	0	11.4
Cost of Core ($M)	381.8	345.9	300.9	289.5

Note that the lower enrichments used in the RBAs were already taken into account in earlier sections of this chapter when fuel costs were determined. They are highlighted here only to show their economic benefit and should *not* be double-counted. Refer to Appendix A for the methodology used in calculating the numbers found in this table.

Two other key factors must be considered when examining the results in Table 2-3. First, savings are based on the assumption that if RBAs were not used that the peripheral assemblies would be of the same composition as the next innermost assembly with no burnable poisons. Second, there is a change in cycle length that accompanies the use of RBA. This change would affect annual fuel costs, as well as the O&M factors discussed in Chapter 3. Since RBA s are already an integral part of the extended core design, the objective of the above table is to show that large savings result from the use of this strategy, not to pinpoint these savings. Thus, only total savings over core life are presented.

The RBA fueling strategy is also advantageous from a neutronics standpoint as it reduces the front end cost increase between the reference cycle cores and the proposed extended cycle cores by about 9% and 4% for the BWR and the PWR. RBAs also eliminate any additional economic and safety concerns that may have arisen with respect to the inherent increase in vessel fluence associated with a core design using increased enrichment fuel, since they yield fluences on the reactor vessel less than current low leakage core designs [M2].

2.5 Potential savings

2.5.1 Reusing peripheral assemblies

An alternative way to realize savings in the front end of the fuel cycle would be to reuse the peripheral assemblies in the core for an additional extended operating cycle. Achieving a lower burnup during the cycle and subject to less flux during operation, these assemblies are predicted to stay within burnup limits should they be used in an extra cycle for the extended cycle cases. The likely strategy for reusing peripheral assemblies would require that only one half of the periphery be replaced each refueling, representing about a 6% and 11% decrease in the amount of fuel that must be fabricated and disposed of in each cycle for the case study BWR and PWR, respectively. This plan would lead to a 6% and 11% financial savings for the BWR and PWR extended cycle cases, equating to about $6.0 and $10.0M/yr. (shown in Table 2-4). These savings are based on the non-RBA core design discussed in the previous section; that is, the peripheral assemblies are at the same enrichment as the next innermost assemblies.

TABLE 2-4: <u>Savings Realized by Re-using Peripheral Assemblies</u>

	BWR Extended Cycle w/out Peripheral Re-use	BWR Extended Cycle w/ Peripheral Re-use	PWR Extended Cycle w/out Peripheral Re-use	PWR Extended Cycle w/ Peripheral Re-use
Core Average Enrichment (w/o U-235)	5.47	5.47	6.87	6.87
Cost of fuel ($/kg)	2815	2815	3611	3611
MTHMU necessary in Rx	135.5	127.0	85.4	76.0
Total cost of core ($M)	381.4	357.5	308.4	274.4
Annual fuel cost ($M/yr.)	95.8	89.8	89.4	79.5
Annual savings from peripheral re-use strategy ($M/yr.)	0	6.0	0	9.9

The RBA fueling strategy could not be implemented using this strategy, since the low enrichment in the outer pins would not sustain sufficient reactivity in the periphery for two consecutive extended cycles. Thus, the reuse of peripheral assemblies and use of RBA are mutually exclusive options. Use of RBA has been chosen as the preferred option because it presents comparable direct economic benefit to re-use of peripheral assemblies ($10M/yr. and $3.3M/yr., respectively) while decreasing vessel fluence to lower, more acceptable levels than periphery re-use [M2]. In addition, 96 calendar months of operation (representing re-use of peripheral assemblies in a 48 calendar month cycle) would undoubtedly challenge fuel endurance limits such as waterside corrosion and rod internal pressure.

2.5.2 New enrichment technologies

Despite the fact that the enrichment process represents the largest portion of fuel costs, there is hope for savings in this area. While current enrichment plants use gaseous diffusion or centrifuge technology as a means of enriching uranium, other newer technologies promise to cut SWU costs. The most developed of these technologies, Atomic Vapor Laser Isotopic Separation (AVLIS), which is predicted to cut the cost of SWU in half by some proponents, could be a way to alleviate high enrichment costs. Other enrichment processes such as Molecular Obliteration LIS (MOLIS) and Chemical Reaction by Isotope Selective Laser Activation (CRISLA) promise even lower unit enrichment costs on the order of $10/kg SWU [E2].

Since no accurate estimate can currently be made as to how much SWU costs will actually drop due to these new technologies, a parametric study has been performed on fuel costs for extended operating cycles, shown in Figures 2-9 and 2-10. These two figures show that as the unit cost of enrichment, or SWU costs, decreases, the rate at which fuel costs for the extended cycle decrease is greater than the rate at which reference cycle fuel costs decrease. This means that as SWU prices drop, so does the margin between the extended and reference cycles. Consequently, the extended cycle becomes more attractive, as the benefits from the O&M factors will have more of an impact. Thus, there is a unique advantage to an extended cycle with respect to low SWU costs. From this graph, it can be shown that if SWU costs are indeed cut in half by AVLIS technology, the difference in fuel costs between the two cycles decreases by about $8 and $10M/yr. (from a difference ~$33M/yr in both cases at $110/kg SWU) for the BWR and PWR, representing a significant savings. Another savings that the above-mentioned new enrichment technologies would introduce would be the elimination of the conversion to UF_6 that is necessary with current gaseous diffusion technology. Since AVLIS requires metallic uranium feedstock, which would lead to new costs, our assumption here is that these positive and negative cost increments would cancel.

Figure 2-9: Effect of New Enrichment Technologies on Fuel Costs for the Case Study BWR

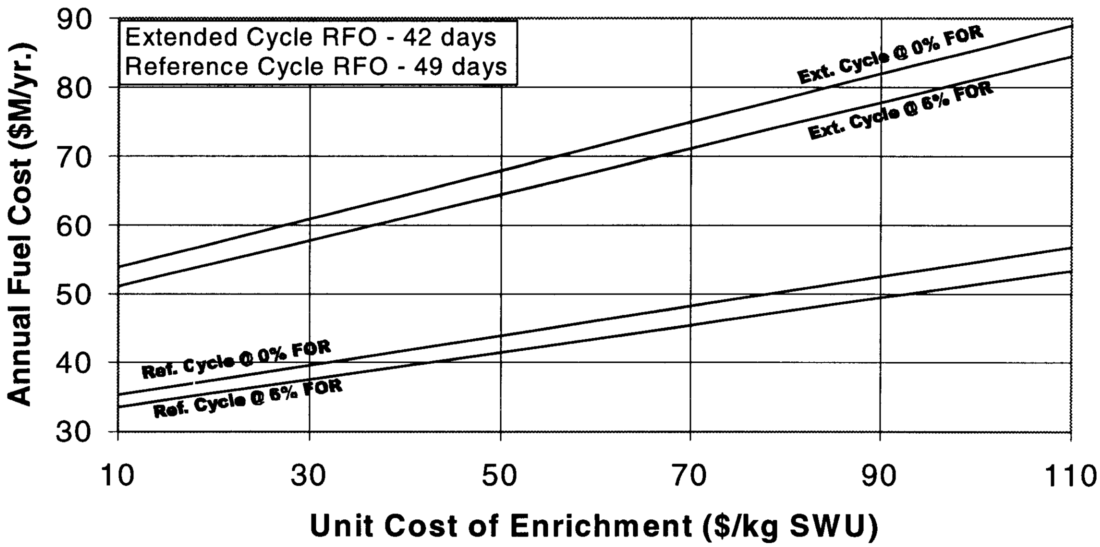
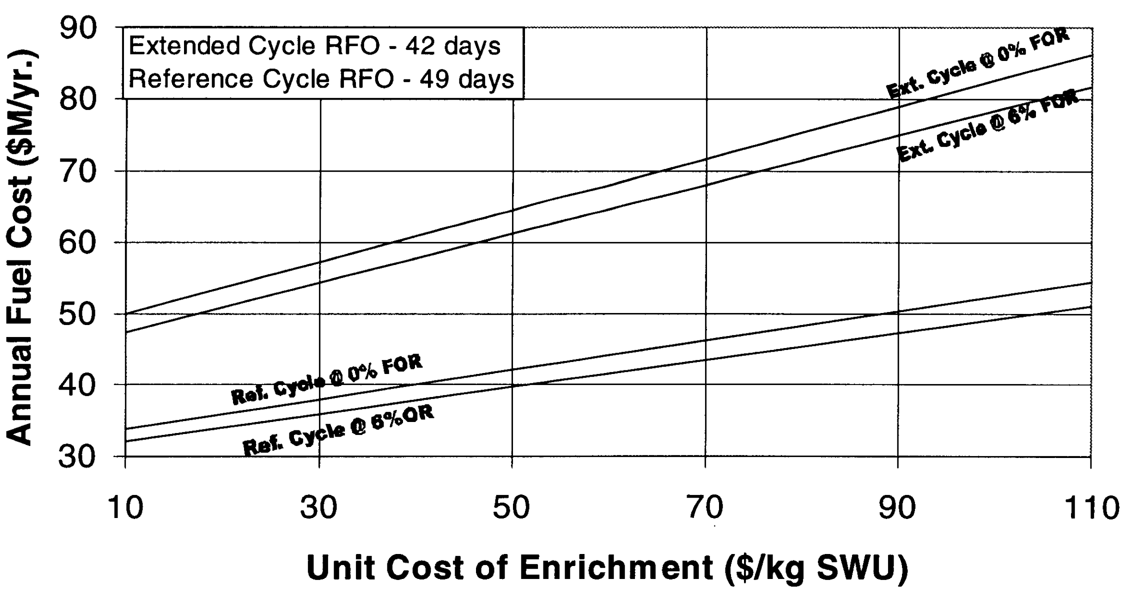


Figure 2-10: Effect of New Enrichment Technologies on Fuel Costs for the Case Study PWR



Additionally, it may be possible to strip tails to much lower concentration with new enrichment technologies, i.e. AVLIS, with the maximum realizable savings occurring when the enrichment of the tails is zero, i.e. $X_w \to 0$. This would reduce the necessary feed into the enrichment process by an amount estimated as follows:

$$\frac{F}{P}=\frac{X_p-X_w}{X_N-X_w} \qquad \{2\text{-}3\}\ \text{(from Ref. [B1])}$$

hence

$$\frac{F'}{P}=\frac{X_p}{X_N} \text{ when } X_w=0\text{, thus}$$

$$\frac{F'}{F}=\left(\frac{X_N-X_w}{X_N}\right)\left(\frac{X_p}{X_p-X_w}\right) \qquad \{2\text{-}4\}$$

For the BWR reference cycle:

$$=\left(\frac{0.711-0.25}{0.711}\right)\left(\frac{4.13}{4.13-0.25}\right)$$
$$=0.69$$

For the BWR extended cyle:

$$=\left(\frac{0.711-0.25}{0.711}\right)\left(\frac{4.92}{4.92-0.25}\right)$$
$$=0.68$$

For the PWR reference cycle:

$$=\left(\frac{0.711-0.25}{0.711}\right)\left(\frac{4.39}{4.39-0.25}\right)$$
$$=0.69$$

For the PWR extended cyle:

$$=\left(\frac{0.711-0.25}{0.711}\right)\left(\frac{6.53}{6.53-0.25}\right)$$
$$=0.67$$

Hence, a further potential savings of ~30% of the ore purchase cost exists for both cases: about \$4.5M/yr. and \$4.2M/yr. for the BWR and PWR reference cycles and \$7.3M/yr. and \$7.1M/yr. for the BWR and PWR extended cycles; hence a net savings of \$3M/yr in both cases.

Although the cost saving factors presented above look promising, it must be reiterated that they are at this point, purely hypothetical.

2.5.3 Alternatives to direct disposal

2.5.3.1 DUPIC

While some additional disposal cost concerns are raised as a result of implementing an extended refueling cycle, alternatives to current disposal practices need to be explored, such as the Direct Use of spent PWR fuel in CANDU (DUPIC) [R1, T1]. Although currently prohibited by U. S. federal regulations, the reprocessing necessary to implement the DUPIC plan is not the same as traditional fuel reprocessing. Rather than completely reprocessing and enriching the fuel, DUPIC involves dry processing in which fuel assemblies are opened, re-pelletized, and re-assembled for use in CANDU reactors. Since the spent fuel from the extended cycle core would have a U-235 enrichment of between 2-2.5 $^{w}/_{o}$ plus a fissile plutonium content of ~1$^{w}/_{o}$, it would be an excellent candidate for the DUPIC process. While CANDU reactors now use 0.711 $^{w}/_{o}$ fuel, the enrichment level of the spent fuel could be readily diluted to accommodate the reload limit for these reactors, currently between 0.9-1.2 $^{w}/_{o}$. Although this concept has yet to be fully developed and would involve a myriad of regulatory, licensing, and capital costs as well as an extensive economic analysis, this may be a way that some of the front end costs of the extended fuel cycle core could be compensated. In addition, DUPIC would reduce not only the amount of CANDU spent fuel (by as much as a factor of three) and save on natural uranium, but also somewhat reduce the total radiotoxicity of spent fuel.

2.5.3.2 Fuel reprocessing

In addition to DUPIC as a back end means of making up some of the front end fuel cycle costs, the spent fuel from an extended operating cycle, because of its higher enrichment, is a good candidate for the conventional reprocessing that countries such as Japan and France currently perform. Although this idea sounds lucrative, current legal, regulatory, and political barriers cast severe doubts on its feasibility in the U. S. or even by contract with foreign vendors.

Table 2-5: Summary of Fuel Cycle Economic Factors

	Case Study BWR	Case Study PWR
Costs		
Realizable		
Fuel cost increase due to higher enrichment - Increased mass flow rates for the mining and conversion stages due to the greater amount of feed necessary for the enrichment process - Increased fabrication costs due to higher Gd_2O_3 and use of IFBA in the fuel	\$33.1M/yr.	\$32.9M/yr.
Transportation costs- - Increase in the number of fuel assemblies that must be transported over a short period of time raises concerns about whether or not the logistical capability of plants will need to be increased	UND*	UND*
Transition cycle strategy	0-\$12.3M/yr.**	0-\$7.9M/yr.**
Change in control rod worth necessary to run core	UND	UND
Change in annual volume of spent fuel assemblies (based on dry cask storage)	\$0.76M/yr.	\$0.16M/yr.
Savings		
Realizable		
Radial Blanket Assembly (RBA) fueling strategy	Already counted	in fuel cost
Potential		
Re-use of peripheral assemblies (alternate to RBA, not additional)	\$6.0M/yr.**	\$9.9M/yr.**
Innovations in enrichment technologies, i.e. AVLIS - cutting enrichment costs by 50% - tails stripping	 \$8.0M/yr.** \$3.0M/yr.**	 \$10.0M/yr.** \$3.0M/yr.**
DUPIC	UND	UND
Fuel Reprocessing	UND	UND
NET, COSTS MINUS SAVINGS (realizable)	**\$33.9M/yr.**	**\$33.1M/yr.**

*UND - Undetermined at this time

** - Not included in net value because of their uncertainty

2.6 Summary

In this chapter, the fuel cycle costs associated with implementing an extended operating cycle have been assessed and identified as realizable and potential. These expenses are summarized in Table 2-5. The realizable net costs are estimated at an additional \$33.8M/yr. and \$33.2M/yr for the BWR and PWR, respectively, representing a large portion of the penalty that plants would experience when using an extended refueling cycle. The increase in the fuel enrichment is the factor responsible for the largest component of this cost increase. While the increase in fuel costs necessary to operate an extended cycle seem high, new, cheaper enrichment technologies hold the greatest promise for mitigating these costs and making extended cycles economically attractive. While viable ways to cut back on these costs have been presented, considerable savings will have to be realized on the O&M side of the ledger if the proposed extended cycles are to be cost beneficial.

CHAPTER 3: OPERATIONAL & MAINTENANCE (O&M) ECONOMIC FACTORS

3.1 Introduction

As shown in the previous chapter, there are significant fuel cycle costs associated with implementing an extended refueling cycle strategy. These costs are all incurred in the interest of increasing the length of time for which a reactor plant can operate without having to shut down, and mainly arise from the need for increased fuel enrichment. In this chapter, two compensatory factors, reducing forced outage rate and limiting the time spent during shutdown will be addressed in the context of their unique application to extended cycles. These two factors must be optimized in coordination with the fuel design and management if capacity factor is to be improved and a net economic benefit realized. The savings in these two areas must be significant enough to cover the increased fuel expenses if this project is to provide the nuclear power industry with an economically attractive alternative to current operations.

Similar to the fuel cycle economic factors, the O&M aspects associated with operating cycle extension will be classified into different cost and savings categories. Other issues that relate to operating cycle extension will also be explored.

3.2 Realizable savings

3.2.1 Outages

Although costly, outages are a necessary part of plant operations. The two types of outages that are encountered in nuclear power plant operations are forced outages (FOs) and planned outages, which can generally be categorized as either refueling outages (RFOs) or planned maintenance outages (PMOs). Similarly the costs of these outages are of two types: material and manpower (M&M) and replacement power costs. During outages, the base-loaded nuclear plants not only lose the capacity to generate revenue from electricity production and accrue M&M costs, but also higher system costs of providing replacement energy for the customer are incurred. Accordingly, the effect that RFOs and FOs have on plant economics will be discussed in this section. The effect of PMOs will not be explored as they vary greatly in length and timing for each individual plant. The framework set up for handling the M&M and replacement energy costs of RFOs and FOs is generically applicable and will serve as the basis for incorporating PMO costs in the future.

3.2.1.1 Avoided refueling outages (RFOs)

One of the keys to achieving an increased capacity factor is decreasing the time spent in refueling outages; the relationship between the number of avoided refuelings, the length of the extended cycle, and the length of the reference cycle to which the extended operating cycle is being compared is:

$$a = \frac{\left(\frac{T_{Ce}}{T_{Cr}} - 1\right)}{\frac{T_{Ce}}{12}} \qquad \{3\text{-}1\}$$

where: a = number of avoided refuelings per year

T_{Ce} = length of extended cycle, calendar months

T_{Cr} = length of reference cycle, calendar months

Thus when comparing the 1-batch, 48 and 41.4 calendar month extended cycles to the nominal 3 batch, 24 calendar month and 2.68-batch, 18 month reference cycles, 0.25 and 0.38 refueling outages per year can be avoided for the BWR and PWR, respectively.

While this metric may serve as a good back-of-the-envelope comparison to show that savings can be achieved as a result of extended operating cycles, it does not take into account the fact that operating cycles of different lengths may well have different RFO lengths. Further, it should be noted that the costs compared in this section are only for the material and manpower (M&M) associated with the refueling outage. The replacement power that must be provided to the grid during a refueling outage is accounted for in the next section and completes the list of cost factors that need to be considered with respect to refueling outages.

The treatment of the M&M costs associated with refueling outages is based on 2 assumptions: (1) longer RFOs will undoubtedly incur more costs and (2) RFO M&M costs are linearly proportional to the length of the RFO. Hence:

$$C = \frac{d * m1}{\frac{T_C}{12}} \qquad \{3\text{-}2\}$$

where: C = annual cost of M&M for a RFO, \$M/yr.

d = length of RFO, days

m1 = daily M&M cost for an RFO, \$M/day

T_C = cycle length, calendar months

Using an estimate of \$0.6M for *m1* above (obtained from recent average values of the price of an outage from an industry expert), a savings of \$8.4M/yr. and \$12.2M/yr. results for the BWR and PWR extended cycle cases, respectively, as shown in Table 3-1 below.

Table 3-1: Comparison of Refueling Outage Maintenance and Manpower Costs

	BWR Reference Cycle	BWR Extended Cycle	PWR Reference Cycle	PWR Extended Cycle
Refueling Outage Length (days)	49	42	49	42
M&M cost per RFO day (\$M/day)	0.6	0.6	0.6	0.6
Cycle Length (calendar months)	24	48	18	41.4
C: Annual Cost of RFO M&M (\$M/yr.)	14.7	6.3	19.6	7.3
Savings (\$M/yr.)	0	8.4	0	12.3

Since the costs and associated savings discussed in this section are heavily dependent upon the lengths of the refueling outages assigned for the different cycles, a brief explanation of how these values were chosen follows. The reference cycle case RFO lengths are based on the 1996 U. S. LWR fleet mean RFO, whereas the extended cycle case RFOs are based on the predictions for reasonably achievable practice made by another member of the extended cycle group at MIT [T2, M4]. In reviewing these numbers, the discrepancy in the length of RFO with respect to the cycle length is apparent; that is, the prediction for the RFO length for the extended cycle is shorter than that for the reference cycle. While this skews the economic results in favor of an extended cycle, one must consider that the success of an extended cycle depends heavily upon the most efficient planning and use of resources, such as minimizing the number of RFO days and increasing the amount of on-line maintenance, to maximize the benefits associated with such a strategy. Thus we will examine whether the extended cycle, even with a differential benefit in RFO, can compete with current practice.

3.2.1.2 Reduction in forced outage rate (FOR)

Central to the impetus for the investigation of extended operating cycles is the hypothesis that there is an inherent benefit with respect to forced outage for a longer operating cycle. This rises principally from the idea that infant mortality effects are overcome and not revisited as often in an extended operating cycle, translating into a lower forced outage rate (FOR). The costs associated with a given FOR can be found from:

$$D = \frac{[(T_C * 30.4375) - T_R] * \left(\frac{FOR}{100}\right) * m2}{\frac{T_C}{12}} \qquad \{3\text{-}3\}$$

where: D = annual cost of M&M for a forced outage, \$M/yr.

T_C = cycle length, calendar months

T_R = refueling outage length, days

FOR = Forced Outage Rate, %

m2 = daily M&M cost for a forced outage, \$M/day

Using an estimate of \$0.1M for *m2* above (obtained from an estimate made by an industry expert), a saving of \$0.9M/yr. results for both the case study BWR and PWR, respectively, shown in Table 3-2. Although these amounts are not as significant as for the M&M costs associated with a RFO, they should be included for completeness.

Table 3-2: Comparison of Forced Outage Maintenance and Manpower Costs

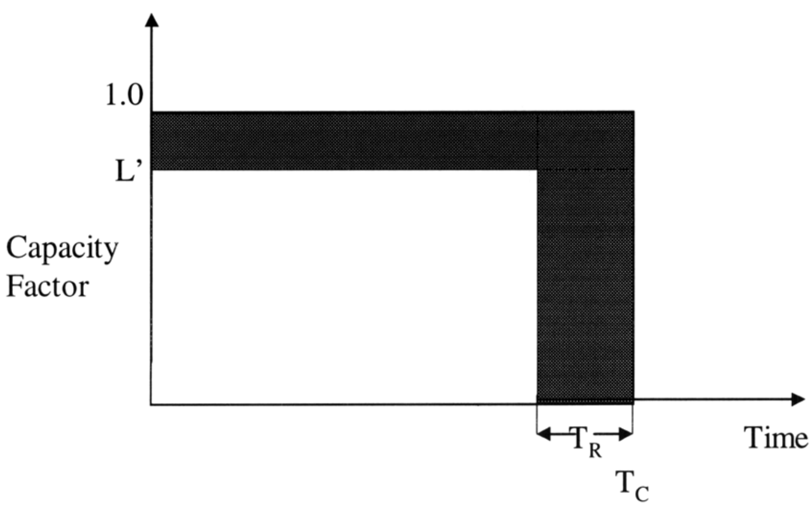
	BWR Reference Cycle	BWR Extended Cycle	PWR Reference Cycle	PWR Extended Cycle
Forced Outage Rate (%)	6	3	6	3
Refueling Outage Length (days)	49	42	49	42
M&M cost per FO day (\$M/day)	0.1	0.1	0.1	0.1
Cycle Length (calendar months)	24	48	18	41.4
D: Annual Cost of Forced Outage M&M (\$M/yr.)	2.0	1.1	2.0	1.1
Savings (\$M/yr.)	0	0.9	0	0.9

The values for the FORs used in the reference cases were chosen by using average (or representative) values for the median plant in the U. S. LWR fleet in 1996, in the same manner as all of the other reference cycle parameters [T3]. For the extended cycle case, the FOR values were granted a margin under that which exists for current practice, consistent with the hypothesis that there is an inherent benefit with respect to forced outage for extended operating cycles. The margin of 3%, however, is a larger reduction than data currently supports, but it is adopted to examine whether, even with such a large differential FOR benefit, the extended cycle can compete with the reference cycle.

3.2.1.3 Replacement energy

Since the key objective of this project is to optimize the capacity factor in order to minimize the cost of electricity to the consumer, a study must be made of the replacement energy that must be provided to account for the plant not operating at a 100% capacity factor. Shown in Figure 3-1, a schematic of capacity factor versus time shows the generated and replacement energy (shaded region) for an operating cycle:

Figure 3-1: Schematic of Generated and Replacement Energy for a Typical Operating Cycle



From this figure, the following relationship for replacement energy can be derived (derivation shown in Appendix C):

$$E_R = P * T_C * \left\{ 1 - L' \left(1 - \frac{\left(\frac{T_R}{30.4375} \right)}{T_C} \right) \right\} * 730.5 \qquad \{3\text{-}4\}$$

where: E_R = replacement energy, $kWhr_e$

P = full rated power of plant, kW_e

T_C = cycle length, calendar months

L' = 1 minus forced outage rate = Availability

T_R = length of refueling outage, days

In order to find the annual equivalent cost of this replacement energy, the following relationship can be applied:

$$E = \frac{E_R * \left(\frac{\left(\frac{e_R}{1000} \right)}{\left(\frac{T_C}{12} \right)} \right)}{1E06} \qquad \{3\text{-}5\}$$

where: E = annual cost of replacement energy, \$M/yr.

E_R = replacement energy, $kWhr_e$

e_R = unit cost of replacement energy, mills/ $kWhr_e$

T_C = cycle length, calendar months

Comparing the BWR and PWR reference and extended cycle cases at a replacement energy unit cost of 25 mills/$kWhr_e$, significant savings can be realized with extended cycles as shown in the Table 3-3 below.

Table 3-3: Comparison of Replacement Energy Costs

	BWR Reference Cycle	BWR Extended Cycle	PWR Reference Cycle	PWR Extended Cycle
Forced outage rate (%)	6	3	6	3
Refueling outage length (days)	49	42	49	42
Cycle length (calendar months)	24	48	18	41.4
Capacity factor (%)	87.7	94.2	85.6	93.8
Replacement energy ($kWhr_e$)	2.37E09	2.23E09	2.18E09	2.17E09
Unit cost of replacement energy (mills/ $kWhr_e$)	25	25	25	25
E: Annual cost of replacement energy (\$M/yr.)	29.7	14.0	36.3	15.7
Savings (\$M/yr.)	0	15.7	0	20.6

While this appears to be a significant savings, it is based on a replacement energy unit cost that can vary, depending upon how this cost is defined, whose point of view is adopted (plant operator, system dispatcher, customer), and on the local energy market. In addition, the value of replacement energy costs may vary from outage to outage. In a soon to be deregulated energy market, this cost (as viewed by the plant operator) presently represents the maximum price at which the plant could sell its energy to the power grid and still displace the former provider of the replacement energy, i.e. an infinitesimally smaller value, which will be taken as equality. Although the energy market is currently regulated, de-regulation will be in full practice when the extended cycle would eventually be implemented and thus replacement energy costs will be based on the de-regulated definition. In view of the variability of and uncertainty over this term, a parametric study will be performed in Section 4.4.1 exploring the effect of replacement energy cost on both profitability and the economically optimum cycle length.

3.2.1.4 Reduced radiation exposure

Since most of the radiation exposure that plant personnel receive is during outages, operating at extended cycle lengths would reduce the amount of radiation that the plant workforce receives. This would reap not only health and safety benefits for workers, but also savings for the plant in increased productivity. While the nuclear power industry uses a standard of $10,000 to represent the break even amount it would spend to reduce exposure by 1 person-rem, there is also an insurance benefit of as great as $40,000 per year that could be gained by being better than the industry mean for the Institute of Nuclear Power Operations (INPO) Plant Performance Criterion of Cumulative Radiation Dose [W3].

Greater benefits would be gained for BWRs than for PWRs in reduced radiation exposure through avoided outages, since the cumulative dose during a RFO for a BWR can range anywhere from 20-300 person-rem and values for the PWR are typically between 10 and 20 [J1, M6]. The higher values of cumulative dose for the BWRs are a result of the fact that much of the work that needs to be done during an RFO needs to be done in the containment drywell, a high dose area. The wide range of dose values for the BWRs is due to the differences in age of the plants in the BWR fleet, reflecting the fact that newer plants are typically designed to reduce this cumulative RFO worker dose. Additionally, different water chemistry strategies are also suspected in contributing to this wide range, as innovations in BWR water chemistry aimed at reducing crack growth have increased the amount of Co^{60}, the primary contributor to coolant radiation dose [J1].

3.3 Realizable up-front costs

As with the implementation of any new strategy or technology, the up-front costs associated with the changes to be made require consideration. Assuming that the remaining life of the extended cycle plant is 20 years, these up-front costs can be assessed and levelized over the life of their use to give an equivalent annual expenditure. Assuming a continuous cashflow approach, a continuously compounded discount rate of 10%, and a life over which these costs will be recovered of 20 years, the up-front lump sum cost can be multiplied by ~0.116 to obtain the levelized cost in $/yr. (see Appendix B).

3.3.1 Research and Development (R&D)

In some instances, a significant amount of research and development (R&D) may be needed to develop the means to improve plant systems sufficiently to permit non-stop extended cycle runs. Areas in which R&D must be performed for the extended cycle project encompass five major areas: design of a new core having increased enrichment, an investigation into improving component availability, licensing and regulatory concerns, transition cycle strategy and implementation, and an analysis of the entire project to determine its economic solvency. The up-front licensing costs alone associated with an extended operating cycle have been estimated at a reasonable $97,000 or $11,400/yr., which includes both the licensing changes themselves and their associated training requirements [R2]. Additionally, it is hypothesized that the cost borne by fuel vendors who currently perform much of the licensing and accident analysis is between $150,000 and $200,000 or $17,000 and $24,000 per year [R2]. Since many plants face common problems or use similar fuel, much of the work needed in these categories can be shared, leading to a modest per plant cost.

3.3.2 Plant modifications

Modifications would need to be made to an extended cycle plant to increase the number of on-line surveillances. This means that equipment needs to be made more user-friendly and accessible for surveillance takers. These modifications may include reducing ambient heat, noise, and radiation. Additionally, redundant equipment may need to be added to some components so that they can perform the intended function while their counterparts are being tested, maintained, and checked. Not only may redundant equipment need to be added, but testing apparatus will also need to be added so that measurements of certain plant parameters may readily be taken on-line.

3.4 Realizable on-going costs

3.4.1 Training and education

In order to ensure that the plant will operate properly with an extended cycle, it is necessary to prepare the workforce for the new operating procedures. This will involve initial training, representing a cost. Further necessary education will be incorporated into the already existing regular training program in place at plants. While this may represent a small cost for the restructuring of the periodic training, it should not significantly alter the frequency of the training, since material related to extended cycle issues would replace old training dealing with current practice issues.

The initial training that workers will require will be in the areas of operations, core refueling, implementation of a new surveillance strategy, and better management practices. Since extended operating cycles have unique concerns with respect to operations, i.e. more in-core reactivity, reactor operators will have to undergo a new training and qualification process on the simulator. This re-qualifying of operators and the associated reprogramming of the simulator has been estimated at a nominal $48,000 or $5,640/yr. [R2]. With the enrichment of the fuel increasing, new procedures for the handling and transportation of the fuel will also need to be developed and disseminated. Once workers understand the changes that will be made to the refueling process, they will need to know how they will implement the improved surveillance strategy and enhancements in quality control to achieve the reduced forced outage rates so necessary for operating at longer cycle lengths. Because there will be more on-line and reduced power surveillances, the plant line-ups that workers will see will differ from past "good practice" and the interdependency between components will increase. Additionally, because of different operational procedures, safety and managerial practices will have to be re-evaluated and most likely re-structured. Although all of these new procedures and their associated workforce education costs will require an expense by the plants, this expense is surely less than the costly downtime caused by uneducated workers improperly operating the plant.

3.4.2 Licensing

Since many new operational practices and limits will be redefined with the implementation of an extended cycle, there will be costs associated with getting these new practices and limits licensed. These costs include research, experimentation, and interacting with the appropriate regulatory agency to get these new facets of nuclear power operation accepted. While some of the licensing concerns may be addressed by R&D, the remaining licensing issues will present an ongoing expense as regulations are changed and plant modifications are made.

3.5 Potential savings

3.5.1 Coastdown

In order to increase the amount of energy from a core designed for a given number of Effective Full Power Months, it is possible to coast down, starting at full power and without forced outage such that there is no loss in cycle capacity factor [D2]:

Figure 3-2: Operating Cycle without Coastdown

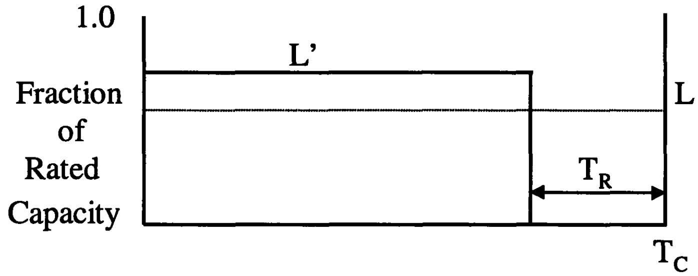
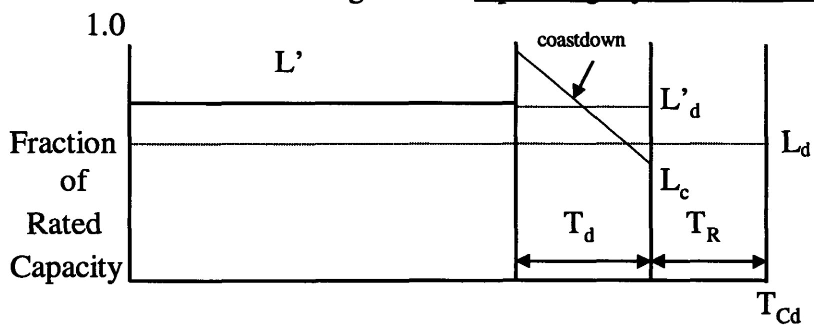


Figure 3-3: Operating Cycle with Coastdown



Given:

$$L'_d = \frac{(1 + L_c)}{2} = \text{Average power during coastdown}$$

where: L_c = power at end of coastdown

Writing an energy balance for the operating cycle without coastdown:

$$LT_C = (T_C - T_R)L' \qquad \{3\text{-}4\}$$

Since it is desired that $L'_d = L$ so that there is no loss in capacity factor:

$$\left(\frac{1+L_C}{2}\right)T_C = (T_C - T_R)L'$$

$$\frac{L_C T_C}{2} = (T_C - T_R)L' - \frac{T_C}{2}$$

$$L_C = 2\left(1 - \frac{T_R}{T_C}\right)L' - 1$$

$$1 - L_C = 2 - 2\left(1 - \frac{T_R}{T_C}\right)L'$$

For the length of coastdown at r%/day:

$$T_d = \frac{1 - L_C}{\left(\frac{r}{100}\right)} = 2\left[\frac{1 - L'\left(1 - \frac{\Delta T_R}{T_C}\right)}{\left(\frac{r}{100}\right)}\right] = 2\left[\frac{1-L}{\left(\frac{r}{100}\right)}\right] \qquad \{3\text{-}5\}$$

Thus, for the extended cycle cases (L'=0.97, 0.97, ΔT_R=42, 42 days, T_C=48, 41.4 calendar months, L = 0.942, 0.938) and assuming r = 0.3%/day and r = 1.0 %/day, the length of break-even coastdown is 38.7 and 12.4 days for the BWR and PWR, respectively. This added energy will not be credited as an economic savings in the present analysis because one can also coast down in the reference cycles. However, it is worth noting that coastdown in the n=1 case does not leave a residual core having a reactivity deficit as is the case for n>1 [D1].

The operational flexibility afforded by coastdown is particularly useful for long, 1 batch cycles to remove some of the long range planning uncertainty as to whether a core will last until a fixed refueling date. However, two key facts detract from the flexibility that coastdown provides for extended cycles. First, as L (capacity factor) increases, T_d (length of break-even coastdown) decreases; hence, the length of coast-down that one can run to maintain a capacity factor consistent with that of the rest of the operating cycle is shorter for a well-run plant. Second, the extended cycle PWR core achieves pin burnups very near the limit of 60 GDW/MTU at End of

Full Power Life (EOFPL), leaving only a margin of 1 Effective Full Power Day (EFPD) before this limit is exceeded [M2].

3.6 Potential costs

3.6.1 Unresolved surveillances

While the goal of extending operating cycles in current LWRs is to increase capacity factor by decreasing the amount of time that a plant is down, the problem of surveillances that are unresolved, i.e. cannot be moved on-line or have their intervals extended to coincide with extended cycle refueling outages, may degrade this unique benefit of extended operating cycles. Two solutions exist to dealing with these unresolved surveillances: (1) performing them during opportunistic forced outage time or (2) taking a scheduled mid-cycle outage.

3.6.1.1 Opportunistic forced outage time

Since only a small percentage of surveillances remain unresolved for the case study extended operating cycle (1.8% of the total 3809 BWR surveillances and 1.4% of the total 3743 PWR surveillances), the time and effort required to perform them would consequently be small [M3]. For the forced outage rates predicted for the extended cycle BWR and PWR (3% for both cases) at least 42.4 and 36.6 days of forced downtime over the course of the cycle are predicted to exist. While this time will not necessarily be continuous, it will more than likely be in a large enough block so that enough time would be available to perform some of the unresolved surveillances. When or how long this forced outage time will occur, however, is not easily predictable. Thus, while forced outage time may present a fortuitous opportunity for performing some of these unresolved surveillances, this time is not guaranteed and a mid-cycle outage of some duration will more than likely be necessary to perform some or all of these surveillances.

3.6.1.2 Mid-cycle outages

Performing a mid-cycle outage, while somewhat costly from both a M&M and revenue loss standpoint, would allow the testing of crucial safety functions and components which become troublesome over the first half of the operating cycle as well as providing a window to perform surveillances which remain unresolved. In addition, surveillances performed during this mid-cycle outage could act as an extra data point for those surveillances which would use performance based testing, decreasing the surveillance burden in the future. Should this mid-cycle outage not be performed, the plant could experience a series of financially debilitating , sequential forced outages that would have to handle the problems that could have been averted with preventive maintenance during a mid-cycle outage.

Performing a mid-cycle outage during the first extended operating cycle at the very least would help prove or disprove the need for these outages in the future. Once the actual data was collected from plant components, especially those that had proven troublesome over longer periods of time in the past or were related to the unresolved surveillances, a more conclusive determination could be made by regulatory officials and plant personnel as to whether or not a need exists to continue this practice. Although this would represent a short term loss of revenues initially, it would be much less expensive than the costs incurred by either subsequent mid-cycle outages or periods of forced outage due to plant problems caused by neglected maintenance. This loss can be estimated as:

$$S = \frac{(E*d)+M}{\frac{T_c}{12}} \qquad \{3\text{-}8\}$$

where: S = annual loss due to mid-cycle outage, $/yr.

E = cost of an Effective Full Power Day (EFPD), $/day

d = length of mid-cycle outage, days

M = material and manpower cost of forced outage, \$/day

T_c = cycle length, calendar months

3.7 Plant-specific issues

While this project has focused on the general economic factors that concern implementing an extended cycle in current LWRs, there still exist some issues that are unique to certain plants which could change the economic desirability of an extended cycle.

3.7.1 Capacity factor

Given that the thrust of extending cycle length is to increase the capacity factor of a plant and subsequently the amount of electricity it can produce at comparable costs, the ability of a plant to improve its capacity factor is important. Studies of available data suggest that extending cycle lengths in plants that do not run at high capacity factors prior to extension is not beneficial [M1]. This suggests that plants should work at improving their capacity factor at shorter cycle lengths before investing time, money, and energy into looking at an extended cycle. While there is currently no benchmark for what capacity factor a plant would need before it would be economically beneficial to extend its cycle length, future analysis should be done to help determine which plants would be suitable for cycle extension.

3.7.2 Rated capacity

In addition to looking at the capacity factor of a plant, the specific power of the plant needs also to be examined. Since the estimates in Table 2-1 for annual fuel cost difference are based on given specific powers, this factor will change for different plants, especially since many plants are upgrading their plant capacity by 5% [P1]. Knowing that fuel costs represent the largest expense in implementing an extended cycle, it is necessary to understand the impact that this plant-specific factor will have on plant economics.

3.7.3 Cost of replacement energy

Since electricity must be supplied to the grid for the margin that exists between the plant output and 100% output at all times, the cost of the energy that will need to be bought as replacement energy becomes a factor worth exploring. While this was quantitatively examined in Section 3.2.1.2, the unit cost used for replacement energy was taken to be a national average of energy costs at 25 mills/kwhre [C3, L1]. Given that this cost varies based on the geographical location of the plant, largely due to the generator plant mix, fuel of choice, seasonal demand, and availability of energy in the region, different replacement energy expenditures will be incurred by different utilities. Hence, what may be economically beneficial for one utility in Region A may prove a detriment for another utility in Region B. This can be illustrated by showing that a small difference in spot energy prices, $10/Mwhre or 10 mills/kwhre, is equivalent to a difference of about a quarter of a million dollars per EFPD in both the PWR and BWR cases. This equates to a difference of ~$23.4M and $17.1M over the length of the extended cycle or ~$5.85M and $5.02M annually for the extended cycle BWR and PWR (assuming replacement energy will need to be generated for all 88.6 and 62.1 days of total outage, respectively). Given the myriad of factors that vary from plant to plant, a plant specific economic model needs to be developed to determine which plants would be best suited for implementing an extended cycle.

3.8 Factors not unique to an extended cycle

In this section, strategies that will enhance the economic benefit of extending cycle lengths will be explored. Centered on a modified surveillance strategy, these factors will not present an economic benefit unique to longer cycles and would benefit current, shorter cycle lengths as well.

However, if cycle length extension is to become a reality, a modified surveillance strategy will need to be developed and implemented as current surveillance practices are not congruent with longer cycle lengths. This will help utilities maximize the economic benefit inherent in operating at extended cycle lengths.

3.8.1 Surveillances

Although not explicitly considered in any of the cost factors considered in this report, surveillances are a major part of plant operations and maintenance (O&M) and play a key role in not only maintaining the availability and reliability of plant components, but also in determining the length of an outage. Three types of surveillances will be explored with respect to extended operating cycles: off-line, reduced power, and on-line. While most off-line surveillance intervals have been extended or surveillances have been moved on-line to be compatible with an extended operating cycle, a few surveillances (~1-2%) remain "unresolved" [M3]. The suggested approach to deal with these unresolved surveillances is to look for engineering solutions to make them more compatible with extended operating cycles; in light of the fact that these solutions do not currently exist, the impact of off-line surveillances on extended operating cycles will be assessed. One technically feasible solution is to perform some of these surveillances at reduced power, an option which will also be evaluated. Finally, the use of on-line surveillances as a necessary means to achieve a maintenance program consistent with cycle length extension (by reducing RFO length and FOR) will be examined. Much work has already been done by Moore and McHenry in References [M1] and [M3] exploring the specifics of the surveillance strategy that would need to be utilized with an extended fuel cycle.

3.8.1.1 Off-line surveillances

While it would be ideal to have no surveillances performed during outages, this is not realistic as there are certain surveillances which must be performed off-line. Since the main problem with performing surveillances during outages is the time that it takes to perform them, a solution needs to be found in order to decrease this time.

One such solution is to perform more surveillances simultaneously during outages. While this would create a need for increased outage planning and manpower, the savings realized by shortening outage lengths would more than likely exceed these costs, as the current average value of an EFPD is ~\$0.66M and \$0.69M (estimated from a national average replacement power cost of 25 mills/kwhre for the case study BWR at 1100 MW_e and the case study PWR at1150 MW_e) and the values for material and manpower used during a forced and refueling outage are \$0.1M/day and \$0.6M/day, respectively [C3, L1]. Successful application of this strategy of optimizing time spent on surveillances during outages can be seen through our Swedish contemporaries, who have managed to limit refueling outage lengths to around 20 days for one of their plants, and the Finnish BWR operators who routinely achieve 10 and 15 day outages for their 12 month operating cycle [K1].

Another approach to the problem of minimizing outage time is to assess the intervals at which off-line surveillances must be performed. If it is found that certain surveillances are being performed too frequently, they can be modified for performance during alternating instead of successive outages, thereby decreasing critical path length to outage completion. Additionally, some surveillances may be found unnecessary and can be eliminated.

By eliminating or decreasing some off-line surveillance intervals, savings would be realized in the areas of planning and labor during outages. This savings could then offset the slight rise in costs which would result from increasing the number of surveillances to be performed simultaneously, with a net benefit of great savings to the utility through decreased outage length.

More unquantifiable savings could also be made through an increase in the lifetime of plant components due to less frequent testing. With human error an ever-present factor in plant maintenance, better off-line surveillance management would eliminate this problem as well as cut long term maintenance costs by improving the availability of plant components and systems.

3.8.1.2 Reduced power surveillances

An approach to reducing the number of off-line surveillances, especially those classified as "unresolved," would be to perform some of these surveillances at reduced power. With this strategy there is the benefit of not only less time necessary for transition to a reduced power state (compared to zero power, hot or cold), but also revenue is still being generated while the plant operates at reduced power. Should a surveillance take longer than predicted, the economic penalty assessed at reduced power is much less than during shutdown.

From a materials standpoint, the reduced power surveillance strategy is also advantageous as the equipment experiences fewer thermal cycles. This both saves on the wear of the component and increases its life. Also of note is the statistic that plant equipment problems often occur on equipment that has been returned to service following shutdown, despite prior proven reliability [M1]. Given both the economic and materials factors, reduced power surveillances present themselves as one of many winning solutions to reducing refueling outage lengths.

Re-performing the economic analysis of using a reduced power strategy (for those surveillances that could be performed using such a strategy) done by Moore et al [M1], we find the following costs for the extended cycle BWR and PWR. Given an 11 day operating window for the reduced power surveillances (10 days of reduced power operation and one day for power ramping up; initial power decrease is assumed to be instantaneous, as it only requires a change in reactivity, i.e. control rod movement), the number of days at each power during the ten day reduced power window are, in order:

⇒ 92% - three days

⇒ 75% - four days

⇒ 50% - one day

⇒ 0% - two days

⇒ 50% - one day (power back up to 100% assuming a linear ramp)

This equates to 4.24 days of lost generating capacity, equivalent to \$2.8M (\$0.7M/yr.) for the BWR and \$2.93M for the PWR (\$0.85M/yr.) using a unit cost of 25 mills/kwhre for replacement energy. While this cost is small, it represents neither a worst nor best case scenario for these surveillances, as they could be performed during a planned outage, increasing the time that the plant was down by extending the critical path, or during opportunistic forced outage time.

3.8.1.3 On-line surveillances

An alternative approach to better management of surveillances during outages is to increase the number of surveillances performed on-line. With less of a workload due to surveillances during outages, the obvious benefit of decreased labor costs arises. Also, with less time committed to off-line surveillances, more time is available for the other pressing and emergent activities that invariably need to be handled during outage time. With this extra time available, the desired outage length is not compromised and outage length could possibly even be reduced for some refuelings.

When implementing an increased on-line surveillance strategy, two main factors must be explored: workforce considerations and planning. Many plants currently perform outages using contracted labor, which often more than doubles their normal workforce. A reduced off-line surveillance strategy would mean a decrease in this specialized, expensive, and less plant-qualified labor.

Additionally, with an increase in on-line surveillances, the current daily workforce at a plant could be more effectively used to meet the plant's surveillance needs while the plant is operating at full power and generating revenue rather than during shutdown, losing money. With less of a time constraint put on the workers to complete assigned tasks on-line rather than off-line where time has a stiff dollar value attached to it, more attention can be paid to the work they perform, increasing not only the quality of the work, but also the life of plant components. Workers would also gain a better understanding of plant operations, equipment, and associated problems as they could afford to spend more time on maintenance related activities. This would yield a long term benefit as they would be broadening their training and educational base, providing for a more knowledgeable and competent workforce. With this increased competence comes not only a decrease in subsequent repair times, but also an increase in the life of the components of the plant as maintenance needs are better met.

Although many savings can be realized from the workforce considerations that arise from implementing an increased on-line surveillance strategy, the increased planning that goes along with this strategy will incur some costs. Given the extremely interdependent nature of parts of a nuclear power plant, planning for on-line surveillances would need to increase since the analysis of how to perform the on-line surveillances would be more complex.

Another factor that plays a significant role in surveillance planning is the increased frequency at which on-line surveillances would need to be performed. Even though workers are likely to be more competent in their jobs due to increased on-line surveillance experience, the possibility for human error still exists. Increased on-line surveillance frequency may well mean amplifying the effect of human error, which is already responsible for 20% of all forced outages [M1].

Table 3-4: Summary of O&M Economic Factors

	Case Study BWR	Case Study PWR
Costs		
Realizable		
Up-front costs - R&D - Plant modifications	 $0.03M/yr. UND*	 $0.03M/yr. UND*
On-going - Training & education - Licensing	 $0.005M/yr. UND	 $0.005M/yr. UND
Potential		
Mid-cycle outages	UND	UND
Savings		
Realizable		
Avoided refueling outages	$8.4M/yr.	$12.3M/yr.
Reduction in forced outage rate	$0.9M/yr.	$0.9M/yr.
Replacement power	$15.7M/yr.	$20.6M/yr.
Reduced radiation exposure to workers due to less frequent outages	UND	UND
Realizable but not unique to an extended operating cycle		
Improved surveillance strategy	UND	UND
Potential		
Coastdown	UND	UND
NET, SAVINGS MINUS COSTS (realizable)	**$25.0M/yr.**	**$33.8M/yr.**

*UND - Undetermined at this time

3.9 Summary

As shown in this chapter, there are significant savings that can be realized by implementing an extended cycle strategy, listed in Table 3-4. With quantified savings of $8.4M/yr.and $12.3M/yr. for material and manpower (M&M) avoided during refueling outages, $0.9M/yr. and $0.9M/yr for M&M avoided during forced outages and $15.7M/yr. and $20.6M/yr. saved on replacement energy during these outages for the extended cycle BWR and PWR, respectively, there exists a potential for the large fuel cost increases to be made up. This trade-off will be discussed in the first part of Chapter 4.

While some of the savings are unique to an extended cycle such as avoided outage savings and replacement energy costs, others such as the improved surveillance strategy could be profitably used in all plants, regardless of cycle length, to improve savings. Given that some of the savings explored were generic, others were unique and suggested the need for a plant specific model to be developed in order for a more accurate economic analysis to be made. While the idea of an extended cycle may be attractive for some plants, it does not necessarily make good economic sense for all plants.

CHAPTER 4: ECONOMIC MODEL

4.1 Introduction

Having identified the major factors associated with extending operating cycles in current LWRs, the focus of this report now shifts to an analysis of a cost model constructed using these factors. Namely, this cost model will be used to: (1) assess the extended cycle case studies discussed earlier and (2) find the economically optimum extended cycle length. Although the original hypothesis was that longer extended cycle lengths will increase economic benefits the most, there may exist a cycle length between current practice and the limit of technical feasibility that will maximize profits. Additionally, parametric studies will be performed on this cost model to account for changes in the economic environment, the energy industry, as well as technological innovation.

4.2 Model construction

Given the trade-off between the fuel cost increases and the savings from the O&M economic factors, we can combine these factors to determine the economic viability of the extended operating cycles. For a first order, yet fairly accurate comparison, only those costs which can accurately be quantified or are of significance are considered: fuel costs (Section 2.2.1), increased spent fuel volume costs (Section 2.2.2.1.2), material and manpower (M&M) costs during a refueling outage (Section 3.2.1.1), M&M costs during a forced outage (Section 3.2.1.2), and replacement power costs (Section 3.2.1.3). With the appropriate inputs for each of these factors, a net cost for any cycle length can be determined and used as a basis of comparison with other cases. Figure 4-1 is a schematic of this cost model which outlines the flow of inputs and derived factors to arrive at the net annual cost results. The relevant input data and equations are documented throughout this report and are compiled in Appendix D.

Figure 4-1: Schematic of Cost Model

INPUTS (Appendix D)

1. Cycle length (calendar months)
2. Forced outage rate (%)
3. Refueling outage length (days)
4. Core mass (MTHMU)
5. Core enrichment loading, including burnable absorbers
6. Plant thermal output (MW_{th})
7. Plant thermoefficiency (%) or Plant electrical output (MW_e)
8. Plant specific power (kW/kg U)
9. Batch index number (n)
10. Core averaged burnup at end of full power life (GWD/MTU)
11. Carrying charge rate (%/yr)
12. Production losses in the front end of the fuel cycle (%)
13. Unit cost of replacement power (mills/kwhre)
14. Unit costs of process steps in the front end of the fuel cycle, to include the effects of burnable absorbers ($/kgU)
15. Unit cost of dry cask storage for spent fuel ($/assembly)

→

FACTORS

A. Fuel Costs ($M/yr.)
B. Cost of increased spent fuel volume ($M/yr.)
C. M&M cost during refueling outages ($M/yr.)
D. M&M cost during forced outages ($M/yr.)
E. Replacement Power Cost ($M/yr.)

→

RESULT

Net Annual Cost ($M/yr.)

Note that for the factors and the result, costs are calculated on a per annum basis ($M/yr.). This is done so that a fair comparison can be made between any set of inputs used to describe an operating cycle strategy at any length, assuming that the project lifetimes are roughly equivalent.

4.3 Case study results

Applying the cost model to the extended and reference cycle cases discussed thus far, the extended cycle BWR is extremely costly compared to the BWR reference cycle, on the order of ~$9M/yr., and the extended cycle PWR enjoys a marginal economic benefit over the PWR reference cycle for the particular set of operating parameters selected. These results are broken down by factor in Table 4-1.

Table 4-1: Comparison of Cost Model Results

	BWR Reference Cycle	BWR Extended Cycle	PWR Reference Cycle	PWR Extended Cycle
A: Fuel Cost ($M/yr.)	53.6	86.7	51.1	84.0
B: Cost of Spent Fuel ($M/yr.)	1.5	2.3	1.0	1.1
C: M&M Costs during a RFO ($M/yr.)	14.7	6.3	19.6	7.3
D: M&M Costs during a Forced Outage ($M/yr.)	2.0	1.1	2.2	1.1
E: Replacement Power Cost ($M/yr.)	29.7	14.0	36.3	15.7
TOTAL ($M/yr.)	101.5	110.4	110.2	109.2
NET ($M/yr.)	**0**	**-8.9**	**0**	**+1.0**

The large discrepancy in profitability is due to two interrelated factors: (1) the electrical output of the case study plants and (2) the cycle length of the reference cases. Since the case study PWR is rated for 50 MW_e output more than the case study BWR, there is more margin for savings for replacement power costs for the PWR. That is, as capacity factor improves for the extended cycle case, there is a (50/1100) ≅5% increased margin of savings for the PWR as compared to the BWR with respect to replacement power costs.

The second of these two factors, the cycle length chosen for the reference cases, contributes to the differences in margin observed for all factors tabulated in Table 4-1. Since the BWR reference case cycle length is 6 months longer than the PWR reference case, the benefits of extending the length of the operating cycle, i.e. spreading out costs over a longer period and better plant performance, are eroded for the BWR when a comparison is made between the reference and extended cycle cases. Although the greater difference between extended and reference case cycle length seen for the BWR would suggest otherwise ($\Delta T_{C\text{-}BWR} = 48\text{-}24 = 24$,

$\Delta T_{C\text{-}PWR} = 41.4\text{-}18 = 23.4$), the results to be discussed in Section 4.4 show that the most benefit from cycle length extension using a batch-loaded core comes during the first couple of months of cycle length addition. After that, the benefit of extending operating cycles becomes less sensitive to cycle length as we approach the ultra-long cycle lengths chosen for the extended cycle cases. This is another advantage that the case study PWR has over the case study BWR. Additionally, for the operational parameters chosen and the different reference cycle lengths, a 6.5% capacity factor improvement is obtained for the extended cycle BWR (as compared to the reference cycle) while the PWR enjoys a 8.2% improvement, equating to increased replacement power savings for the PWR.

Table 4-2: Treatment of Parameters for Case Study Plants Parametric Study

	BWR Reference Cycle	BWR Extended Cycle	PWR Reference Cycle	PWR Extended Cycle
Refueling Outage Length	Varied	Varied	Varied	Varied
Forced Outage Rate	Varied	Varied	Varied	Varied
Cycle Length	Constant	Varied	Constant	Varied
EFPL of core	Varied	Constant	Varied	Constant

The results seen in Table 4-1 are sensitive to the operational parameters, FOR, RFO length and T_C, hence capacity factor, chosen for each case. Since the values assumed for the extended operating cycle are subject to considerable uncertainty, a parametric study was performed to show the dependence of the results on these parameters. Varying the parameters as indicated in Table 4-2, we can see the dependence of the results for the case study BWR and PWR as a function of RFO length and FOR in Figures 4-2 and 4-3.

Figure 4-2: Costs for the Case Study BWR as a Function of Operational Parameters

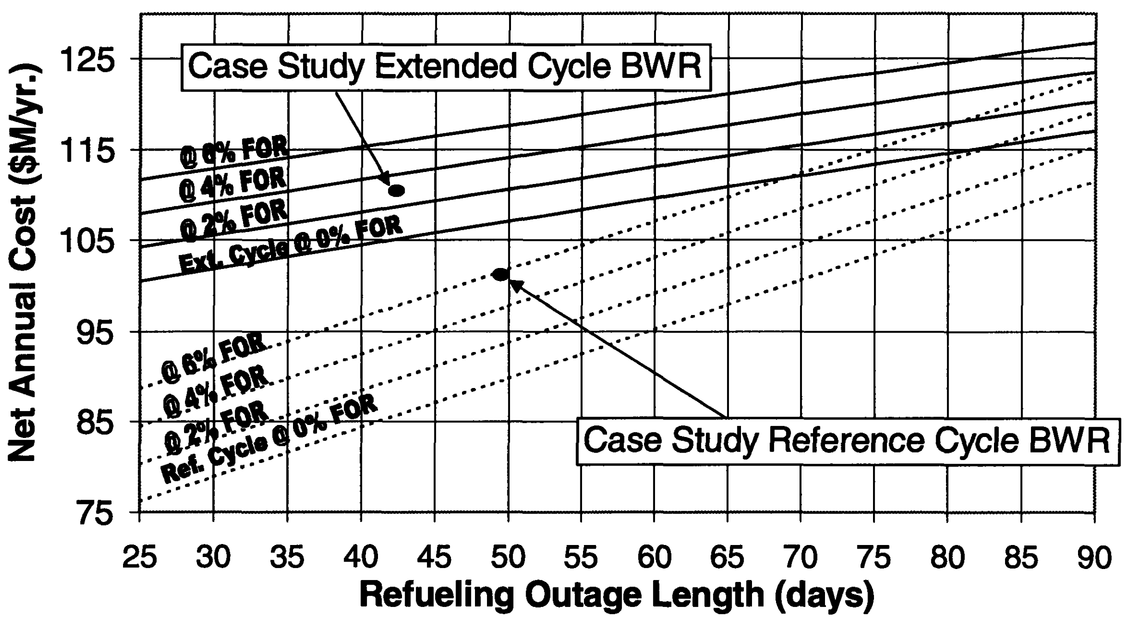
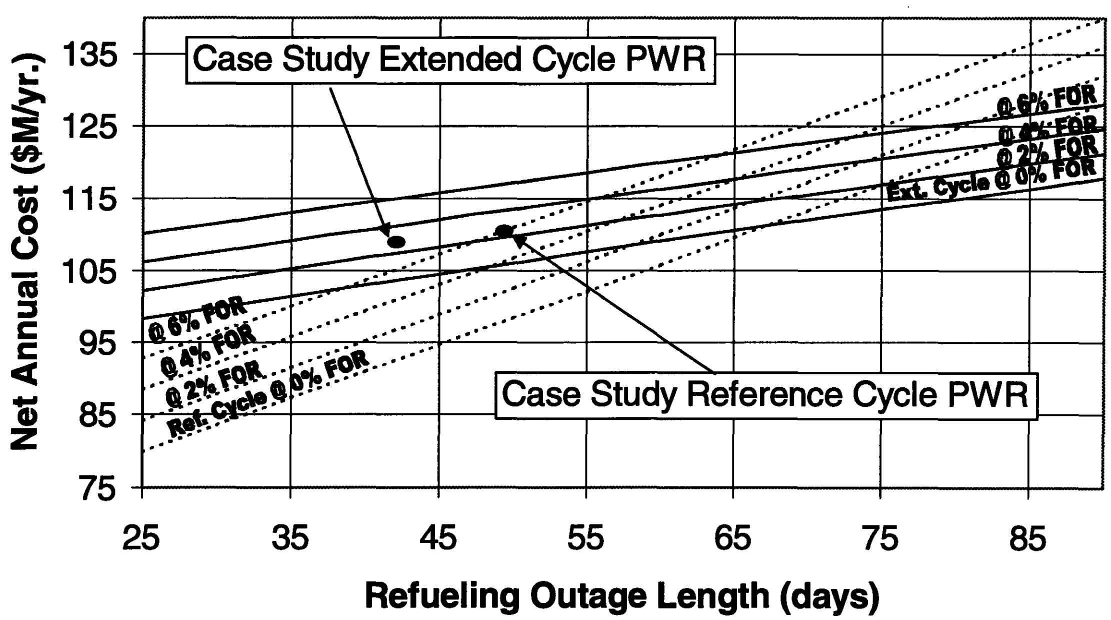


Figure 4-3: Costs for the Case Study PWR as a Function of Operational Parameters



From Figures 4-2 and 4-3, it is apparent that as RFO length increases, extended cycles become more attractive. Intuition supports this result as extended cycles would gain more benefit from avoiding longer refueling outages in both capacity factor change (shown in Figures 1-1 and 1-2) and material and manpower costs. This results mainly from the fact that the savings on an outage cost per annum are greater for longer RFOs, assuming comparable RFO lengths for the reference and extended cycle cases. Thus, the economic potential of extended cycles decreases as RFO lengths continue to decrease as has been the trend within the commercial nuclear power industry.

The economic effect from the difference in FOR that is hypothesized to exist for extended operating cycles can also be shown in Figures 4-2 and 4-3. As the change in FOR between the extended and reference cycle increases, so does the attractiveness of the extended cycle. These figures also show that the effect that this difference in FOR will have is dependent upon the length of the RFOs for each case. Thus, the dependence of the results upon each of these factors is strongly inter-related.

4.3.1 Innovations in enrichment technologies

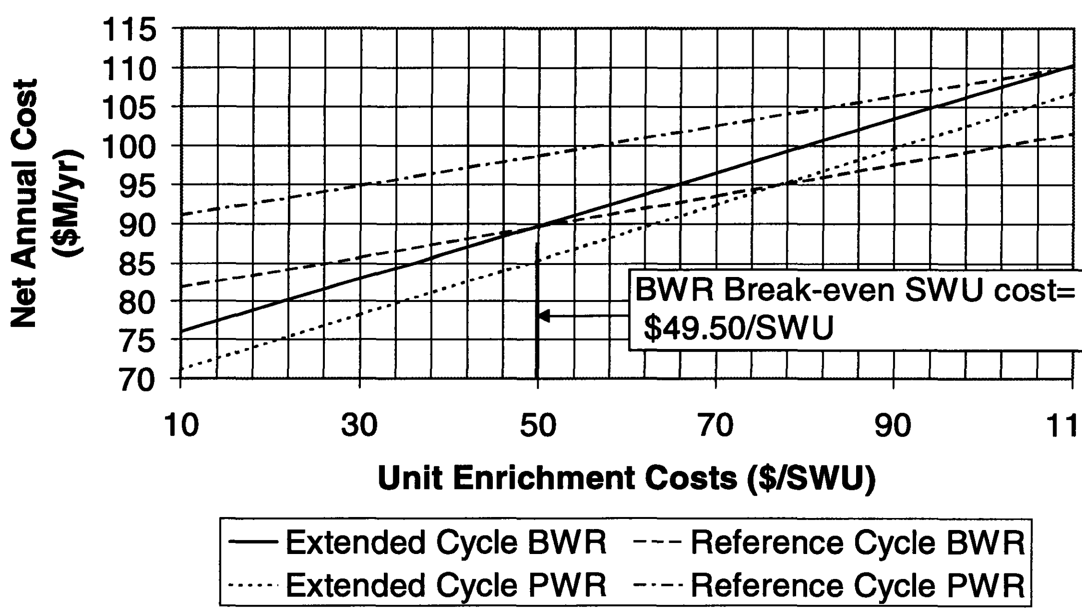
One factor which is likely to change in the near future and holds promise for making both the case study BWR and PWR more economically attractive is decreasing unit enrichment cost as a result of technological innovation in enrichment technologies. Table 4-3 lists the predicted unit enrichment costs of these promising technologies along with those of their current competitors [E2].

Referring to Figure 4-4, the effect that the innovations in enrichment technology will have on the case study BWR and PWR can be seen. While decreasing enrichment costs will make the case study PWR even more attractive at the limit of technically feasible cycle length extension, extending cycle length at the predicted batch loaded optimum for the BWR only becomes profitable when unit enrichment costs reach ~\$49.50/SWU.

Table 4-3: Predicted Prices for Innovations in Enrichment Technology

Process	Process Cost 4 w/o U-235 (\$/SWU)
Mass-Action	
Calutron/EM	>200
Centrifuge	100
Diffusion	120
Laser	
AVLIS (Atomic Vapor Laser Isotope Separation)	87
MLIS (Molecular Laser Isotope Separation)	
MOLIS (Molecular Obliteration Laser Isotope Separation)	50
CRISLA (Chemical Reaction by Isotope Selective Laser Activation)	20
SILARC (Separation of Isotopes by Laser Assisted Repression of Condensation)	10

Figure 4-4: Effect of Innovations in Enrichment Technologies on the Case Study BWR and PWR

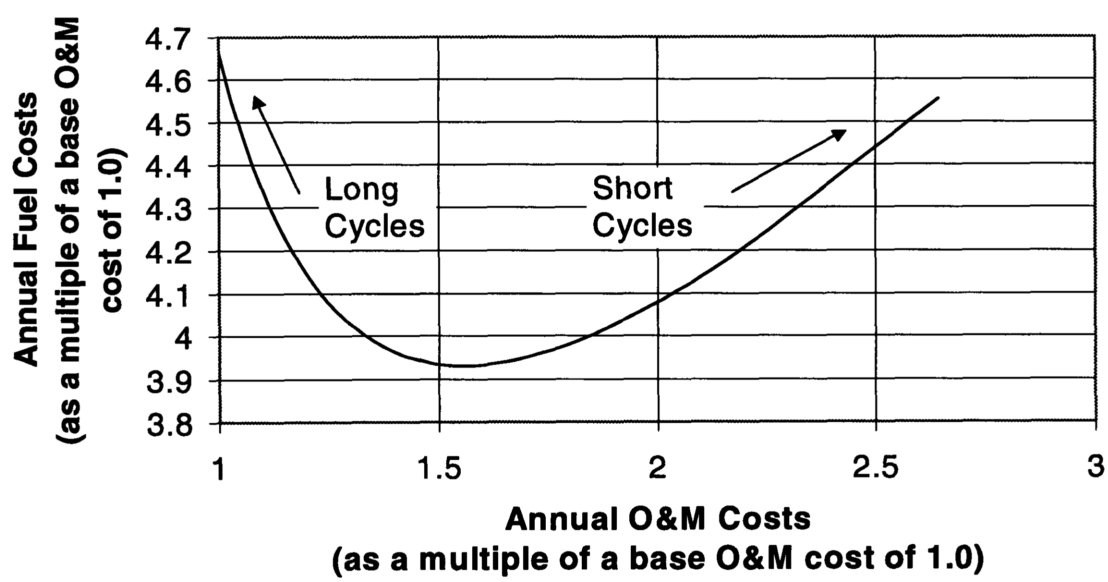


Further, it should be noted that the slopes of the net annual cost with respect to unit enrichment costs are relatively the same for the extended cycle BWR and PWR and also for the reference cycle BWR and PWR. This shows that there is not a distinct, inherent advantage for one over the other with respect to the rate at which SWU costs will make extending cycle length more profitable; that is, a \$10/SWU decrease equals approximately the same profitability change for both.

4.4 Cycle length optimization

Although the preliminary hypothesis of the extended cycle project was that the longer the cycle length the greater the economic benefit, work with the economic analysis has shown that there is some intermediate cycle length, between current practice and the limit of technical feasibility, which may be more profitable. This profitability arises from the non-linear relationship that is found between the fuel cycle economic factors and the O&M economic factors as cycle length is varied, shown generically in Figure 4-5. Using the cost model developed throughout this report and described in Section 4.2, a prediction can be made for where the economically optimum cycle length lies.

Figure 4-5: Generic Cost Trade-Off for a Representative LWR



4.4.1 Parameters

With the operational parameters used throughout Chapters 2 and 3 in the case study plants defined in Table 1-1, a set of parameters for comparing varying extended cycle lengths to current practice must be established. The cycle lengths that will be explored will be from 12 calendar months, the shortest currently employed feasible cycle length, to 75 and 48 calendar months, the maximum technically feasible cycle length for the BWR and PWR, respectively (Note that the maximum technically feasibly cycle length for the BWR is different here (75) than that predicted in Chapter 2 (66), due to the differences in operating parameters assumed for each). While only single batch (n=1) extended operating cycles were explored in the case study plants as a means to extend the cycle length as much as possible, both single and multi- batch fueling strategies will be explored in this section to obtain a broader perspective and understanding of cycle length extension.

With industry working to achieve better availability and with the on-going work being done on availability and reliability within this project, a FOR of 3% can be used as a reasonable value for extended cycle lengths. Additionally, with improvements in outage planning and surveillance management, a 30-day RFO is a realistic parameter, as some plants are able to meet or even better this value today. These values will be used to define a reference set of parameters (with cycle length varying) from this point forward throughout this chapter unless otherwise stated. As with the case studies performed earlier, sensitivity analyses will be performed.

4.4.2 Burnup-enrichment correlation

Given that fuel costs are determined from a specific core design, it would be prohibitively time consuming to design a set of new cores, each at a different cycle length, for use as inputs to the cost model to determine optimum cycle length. Since fuel costs are relatively linear with respect to enrichment (shown in Section 2.2.1.3 and Figure 2-3), the core average enrichment for a given cycle length can be used to predict fuel costs, using a nominal core mass. Fortunately, a correlation can be made between core average enrichment, X_p, and cycle length, expressed in terms of core average burnup at end of full power life, B_1.

Using the following relationships, B_1 can be found as [D1]:

$$B_1 = \left(\frac{n+1}{2n}\right)B_d \qquad \{4\text{-}1\}$$

where:

$$B_d = 30.4375 * n * T_C * L * P \qquad \{4\text{-}2\}$$

where: B_d = batch average discharge burnup, GWD/MTU

n = batch index number

T_C = cycle length, calendar months

L = capacity factor

P = core specific power, kW/kg U, 24.5 and 38.7 for the case study BWR and PWR, respectively

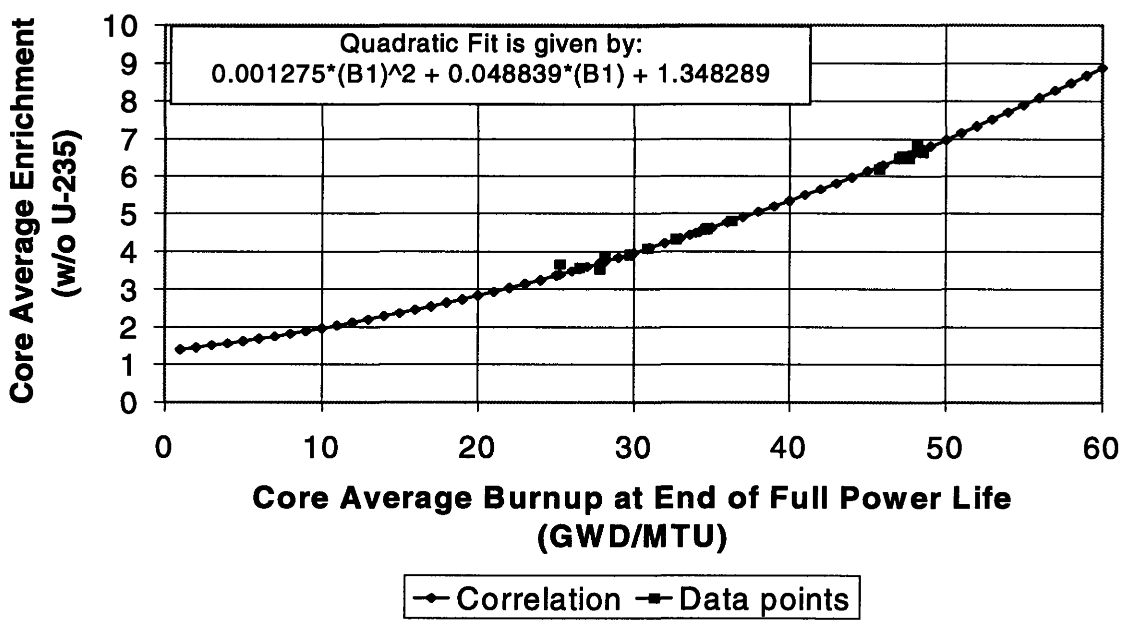
Given the relationship for capacity factor shown in Equation {1-1} and the values for RFO length and FOR discussed in Section 4.4.1, B_1 can be calculated for different batch indices and cycle lengths to find X_p from the correlation.

The $X_p(B_1)$ correlation was found by fitting a quadratic solution to data points of more than 15 different core designs that have been performed with enrichments ranging from ~4 to 6.8 $^w/_o$ U-235 and burnups in the range of ~30-50 GWD/MTU. The quadratic fit was chosen because of the non-linearity of the enrichment-burnup relationship [D1]. Pictured in Figure 4-6, this relationship is:

$$X_p = 0.001275*(B_1)^2 + 0.048839*B_1 + 1.348289 \qquad \{4\text{-}3\}$$

This correlation applies to both the BWR and PWR and has been found to be consistent with industry data. Further, it should be noted that this correlation represents an envelope of best practice, an observation that is consistent with the focus on operating efficiency necessary to the success of extended operating cycles [M5].

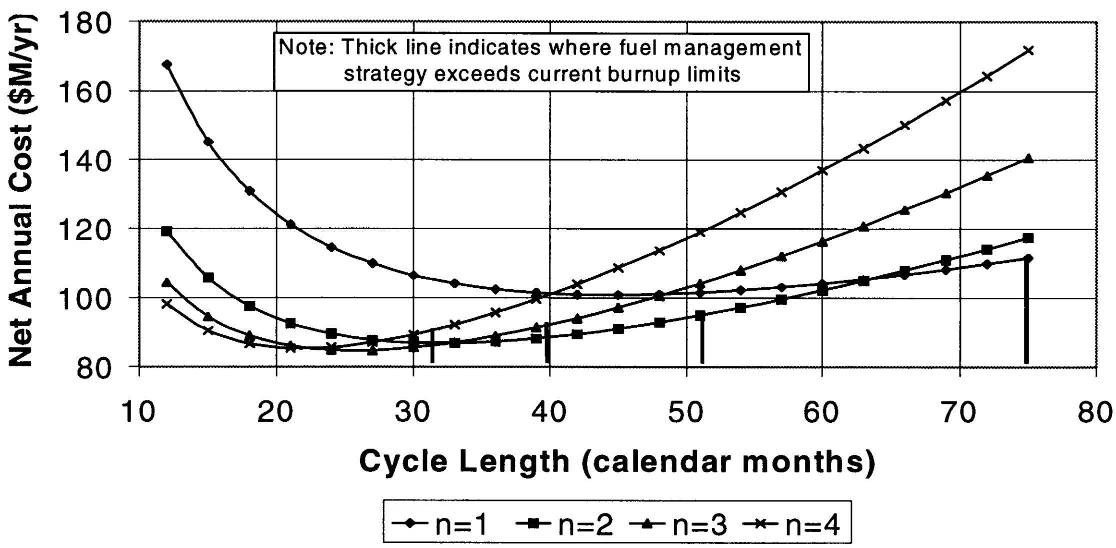
Figure 4-6: Enrichment Burnup Correlation



4.4.3 Results

Using the model, parameters, and methods discussed in this chapter thus far, the cost of an operating strategy can be calculated as a function of cycle length for each batch index number and a set of cost curves results. Figure 4-7 shows these cost curves for the case study BWR. Several interesting conclusions can be made based upon these results. First, multi-batch fuel management is more economically attractive than a single batch strategy for cycle lengths up to ~63 calendar months. Given some of the neutronic limitations resulting from the ultra-high enrichment necessary to make a single batch strategy work and some of the fuel performance problems that are hypothesized to exist from the extended in-core residence time without shuffling, operating for cycles of this length is not likely to be technically feasible. Thus, using an n=1 fueling strategy to achieve an extended operating cycle may not be the best solution.

Figure 4-7: Net Annual Cost as a Function of Cycle Length and Batch Index Number for the Case Study BWR (@ constant FOR = 3% and RFO = 30 days)



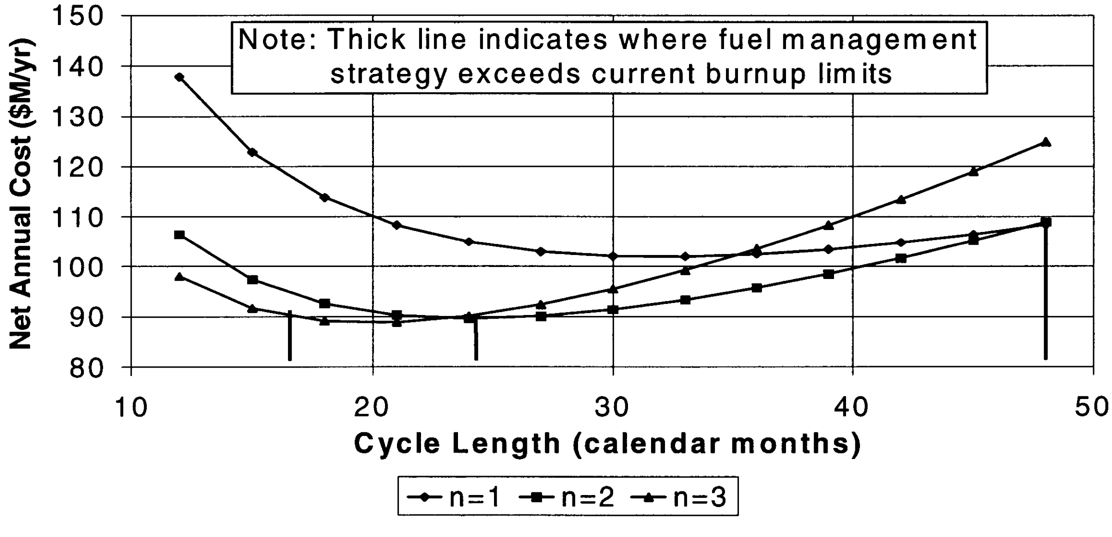
Looking more closely at the each of the cost curves in Figure 4-7, we find the economically optimum cycle lengths at which to operate the respective n-batch fuel management strategies (T_{CBoptn}) to be the following: T_{CBopt1} = 42 calendar months, T_{CBopt2} = 30 calendar months, T_{CBopt3} = 24 calendar months, and T_{CBopt4} = 24 calendar months. Note that while these cycle lengths are not the exact values read from the graphic results, they are the closest economically comparable cycle length divisible by 6 months. This criterion is used because utilities experience much higher demand for electricity during the summer and winter months, plan outages for fall and spring, and consequently keep cycle lengths at which they operate divisible by 6 to ensure that their outages do not occur during peak periods. For the n=1 case, the region on the curve where the optimum is found is relatively flat, suggesting a shorter cycle length for a batch loaded core, say 36 calendar months, is comparable economically (Δ~$1M/yr.) and may present fewer limitations to technical feasibility. Operating at a cycle length less than the optimum yet with comparable economic benefits is not as viable a consideration for the multi-batch fueling strategies since the regions around the optima are not as flat and the fuel is shuffled, mitigating the problems related to neutronic and fuel performance inherent with a batch-loaded strategy.

While Figure 4-7 shows the current burnup limits associated with each fuel management strategy, these limits do not present barriers to implementing the economically optimum cycle length. Comparing cost curves for different n, the most beneficial strategy is at 24 calendar months for n=3 or 4. The cost curves used to make this comparison apply the same operational benefits that are hypothesized to exist for the extended operating cycle (lower FOR, shorter RFO) to current practice. This suggests that utilities would be better off investing in ways to achieve these benefits for current practice, rather than investing in an extended operating cycle where the outcome is less certain and payoff not as great.

Similar cost curves were constructed for the PWR, shown in Figure 4-8. Again, a batch loaded core is only more economically attractive than multi-batch refueling at ultra-long cycle lengths: greater than 48 calendar months in this case. Given that the limit of technical feasibility was found to be at ~41.4 calendar months, using a batch reload strategy for the case study PWR is clearly not the best strategy.

Looking at where the optima for the different strategies lie, we find T_{CPopt1} = 30 calendar months, T_{CPopt2} = 24 calendar months, and T_{CPopt3} = 18 calendar months. Comparing cost curves for different n, it is again shown that the most economically attractive point at which to operate is around the batch fraction and cycle length used in current practice for the case study PWR: T_C = 24 calendar months at n = 2or T_C = 18 calendar months at n = 3. Given that the same operational benefits are given to this current practice as are hypothesized to exist for extended operating cycles, further support is gained for investing in improving current operations instead of less certain, lower benefit extended operating cycles.

Figure 4-8: Net Annual Cost as a Function of Cycle Length and Batch Index Number for the Case Study PWR (@ constant FOR = 3% and RFO = 30 days)



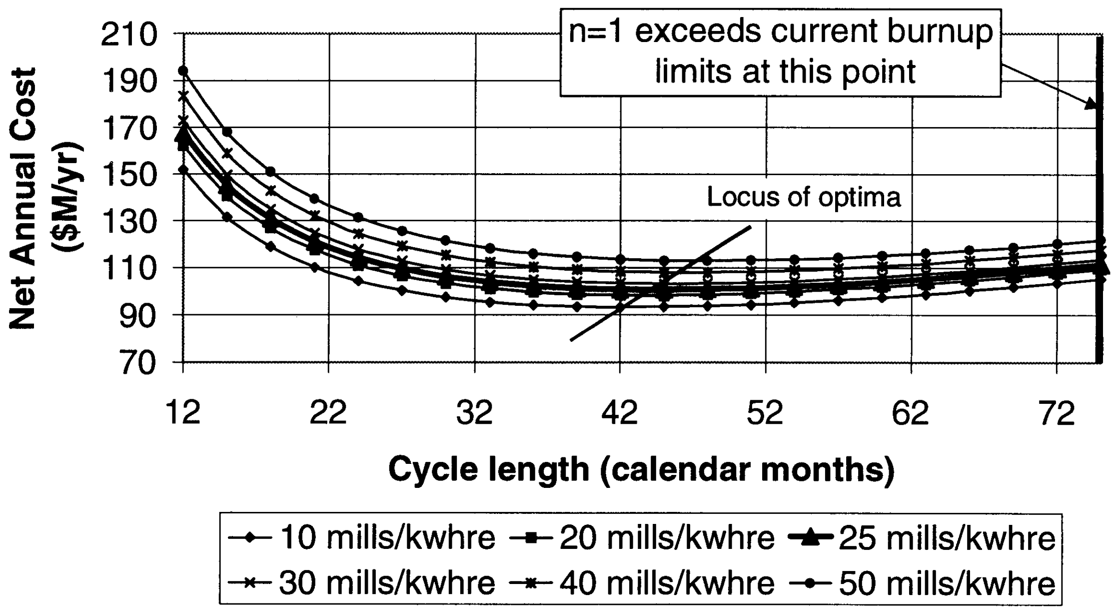
4.4.4 Parametric studies

While the results discussed in the previous section provide insight into the decision of whether or not to implement an extended operating cycle, they are based on static market conditions and predictions of how operating parameters will change for extended cycles. Since markets are often dynamic and predictions invariably flawed, parametric studies have been performed to show the sensitivity of these results with respect to changes in these factors.

4.4.4.1 Replacement energy cost

In a deregulated energy market, replacement energy costs will invariably change. Realizing that replacement energy may be bought and sold based on "spot" market prices which will be too dynamic and unpredictable to model, we examine the effect of a change in the price of replacement energy for the case study BWR for a 1-batch fuel management strategy in Figure 4-9.

Figure 4-9: Effect of Replacement Energy Cost on Cost and Optimum Cycle Length for the Case Study BWR at n=1



As replacement energy unit costs increase, so does the cost of implementing any length operating cycle. This increase decreases with increasing cycle length: about $1M/yr. for every 1 mill/kwhre at a cycle length of 12 calendar months and ~$0.4M/yr. for every 1 mill/kwhre at a cycle length of 75 calendar months (with both cases operating at the defined parameters). This can be explained by the fact that since the same operational parameters (RFO, FOR) are used for all cycle lengths in the cycle length optimization, longer cycle lengths will have a higher capacity factor and therefore require less replacement energy to be provided. Assuming that these parameters will be achieved, this shows that extended operating cycles are more insulated from the effects of changing replacement energy costs. It should be noted that this effect of changing replacement power costs on profitability is independent of batch index number, as shown in Figures 4-10 through 4-12.

As for the effect that replacement energy costs have on the optimum cycle length, it can be seen in Figure 4-9 that as replacement energy costs decrease, so does the optimum cycle length for n=1, on the order of 1.5 calendar months for every 10 mills/kwhre. For increasing n, this ratio decreases only slightly, suggesting that as the number of batches increases (for a fixed cycle length), the optimum cycle length for multi-batch fueling is slightly less sensitive to the effects of a varying replacement energy cost. It is also worthy to note that current burnup limits do not present any barriers to achieving the optimum cycle length for any replacement energy cost.

Figure 4-10: Effect of Replacement Energy Cost on Cost and Optimum Cycle Length for the Case Study BWR at n=2

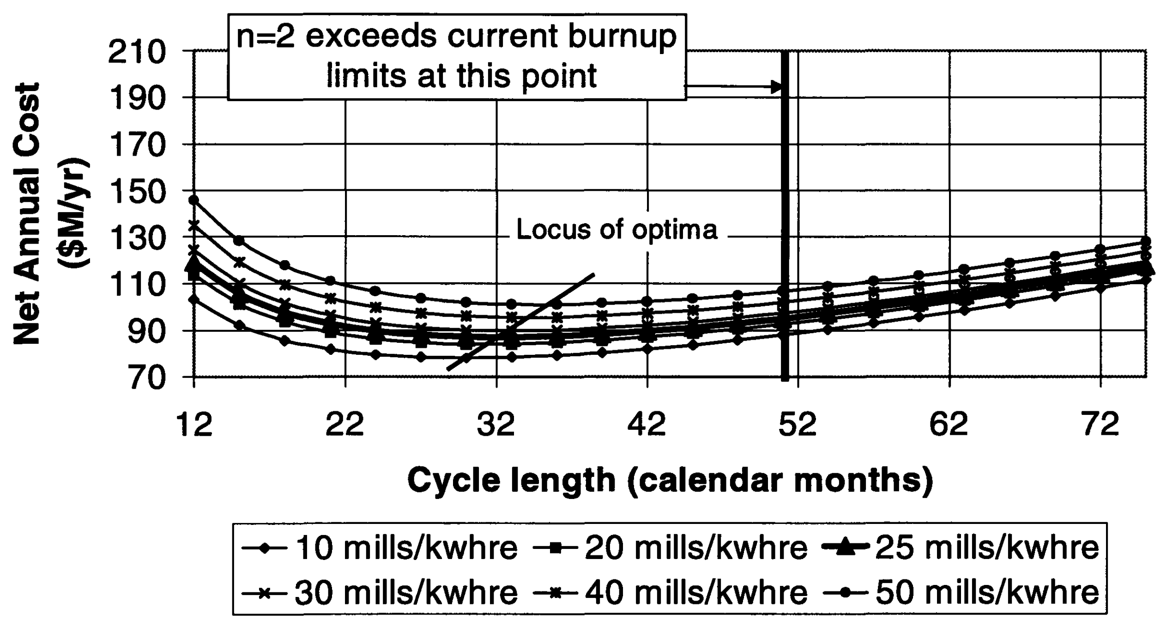


Figure 4-11: Effect of Replacement Energy Cost on Cost and Optimum Cycle Length for the Case Study BWR at n=3

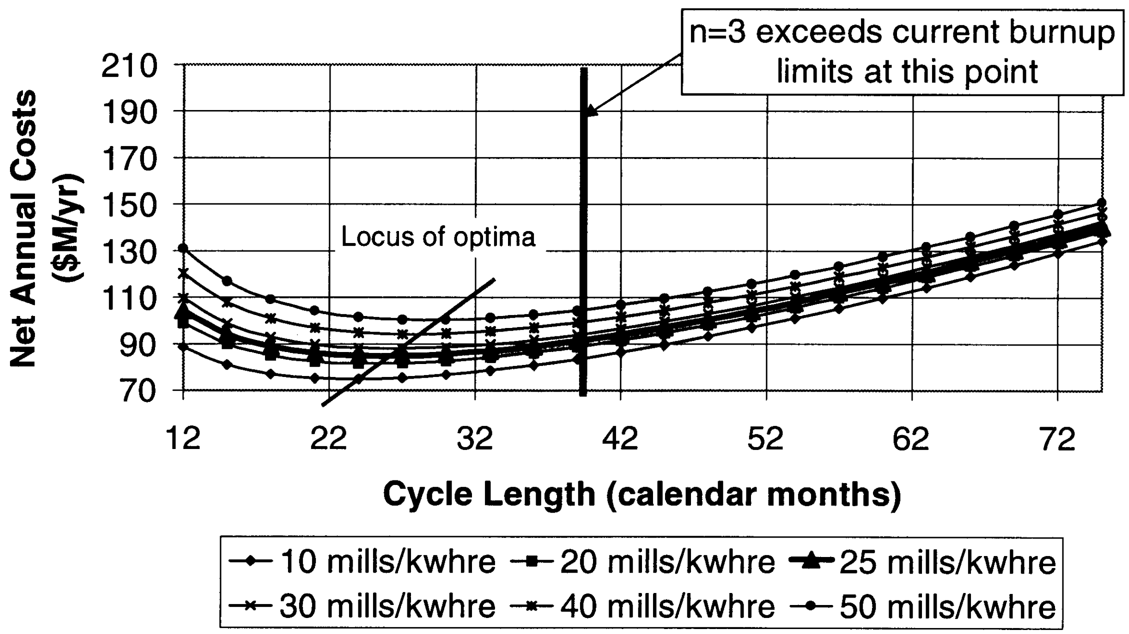
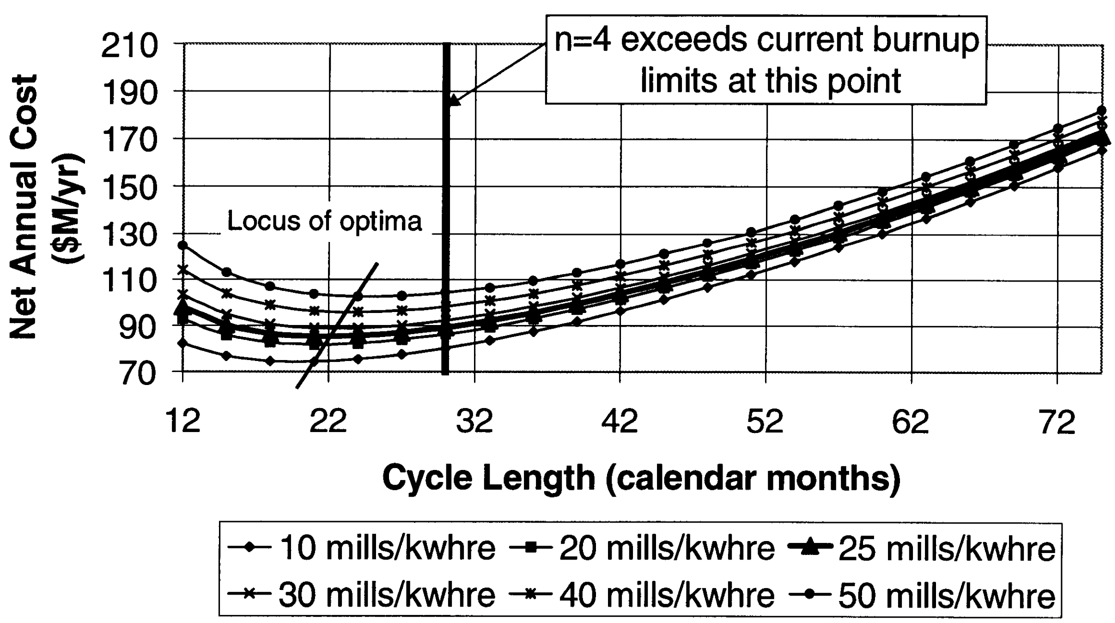


Figure 4-12: Effect of Replacement Energy Cost on Cost and Optimum Cycle Length for the Case Study BWR at n=4



The same effects on total cost with respect to increasing replacement energy costs are experienced by the case study PWR, but with a different ratio: ~\$1.1M/yr. for every 1 mill/kwhre at a cycle length of 12 calendar months and \$0.5M/yr. for a cycle length of 48 calendar months. The discrepancy between the PWR and BWR for this effect can be explained by the fact that the case study PWR is rated at 50 MW_e more than the case study BWR, meaning that more replacement energy must be replaced for a given capacity factor. The decrease in sensitivity to replacement energy costs as cycle length increases shown for the case study PWR supports the same effect that was observed for the BWR and thus suggests that this effect is inherent to extended operating cycles. It should be noted that this effect of changing replacement energy costs on profitability is again independent of batch index number for the PWR, shown in Figures 4-13 through 4-15. It must also be noted that these differences are not endemic to the technical differences between a BWR and PWR, but are only a function of the differences in rated capacity of the case study plants chosen.

Figure 4-13: Effect of Replacement Energy Cost on Cost and Optimum Cycle Length for the Case Study PWR at n=1

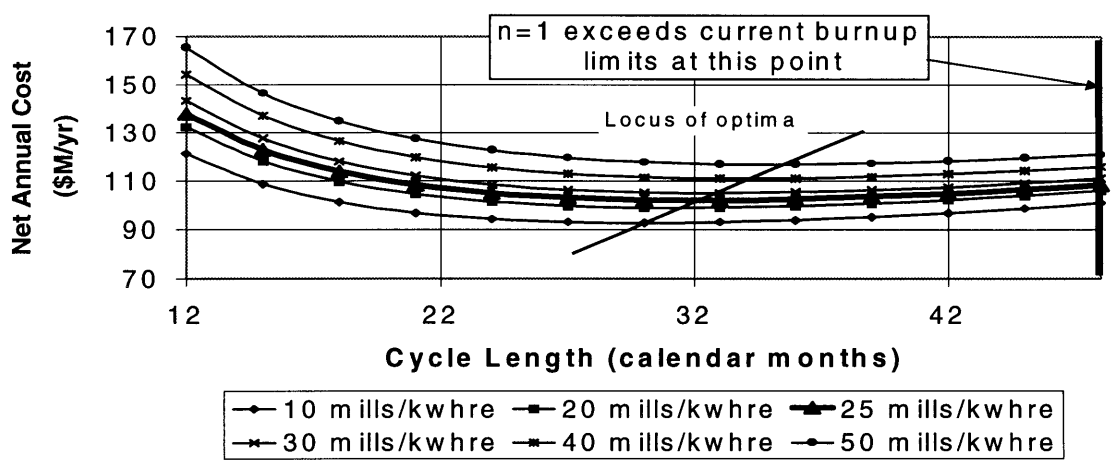


Figure 4-14: Effect of Replacement Energy Cost on Cost and Optimum Cycle Length for the Case Study PWR at n=2

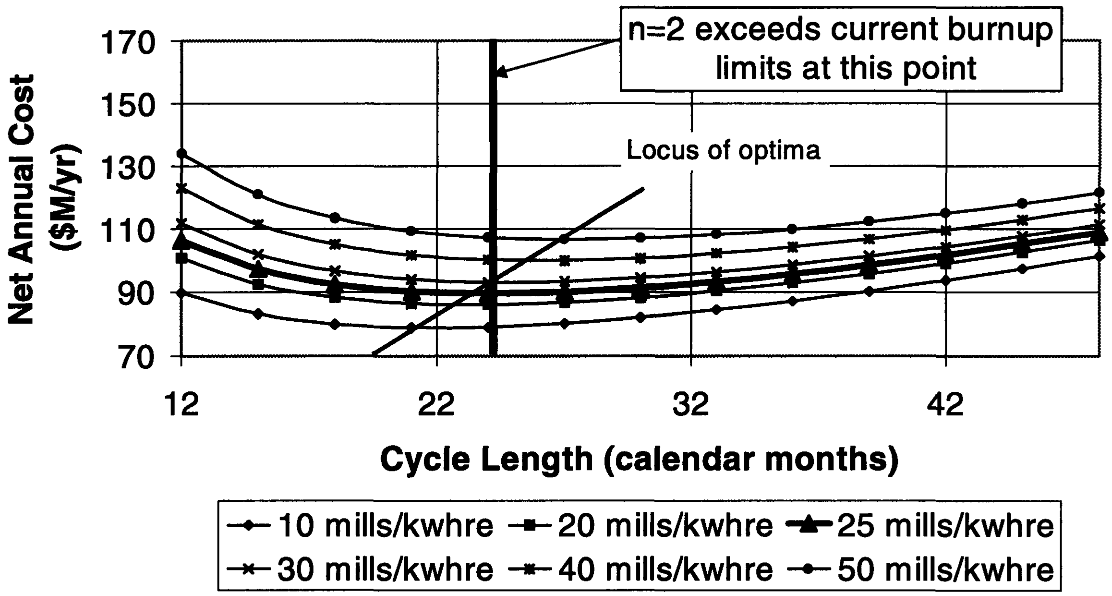
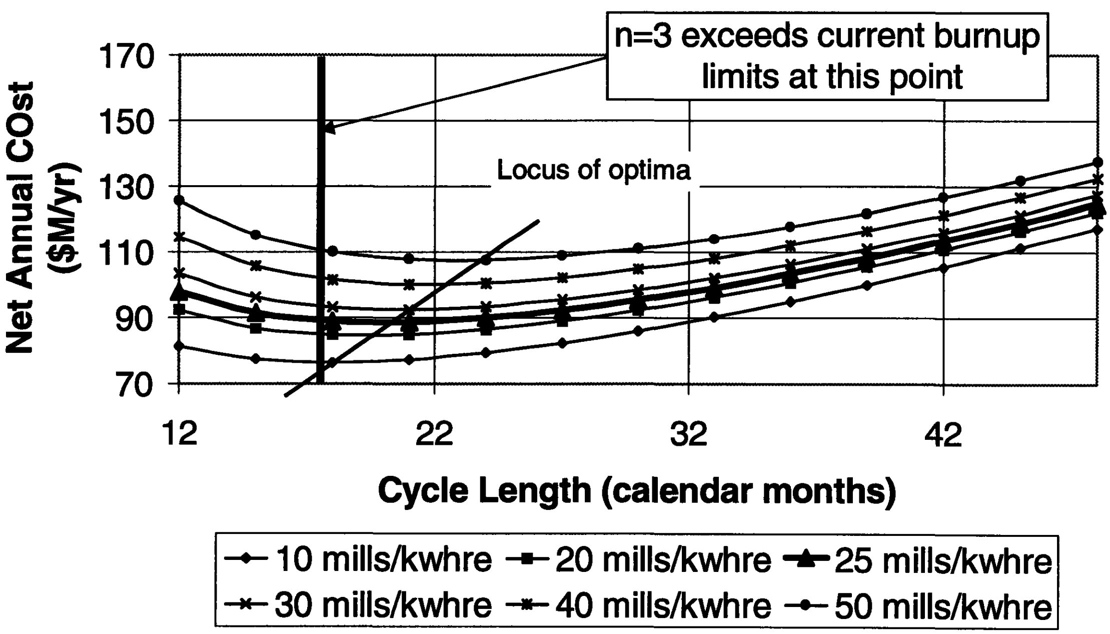
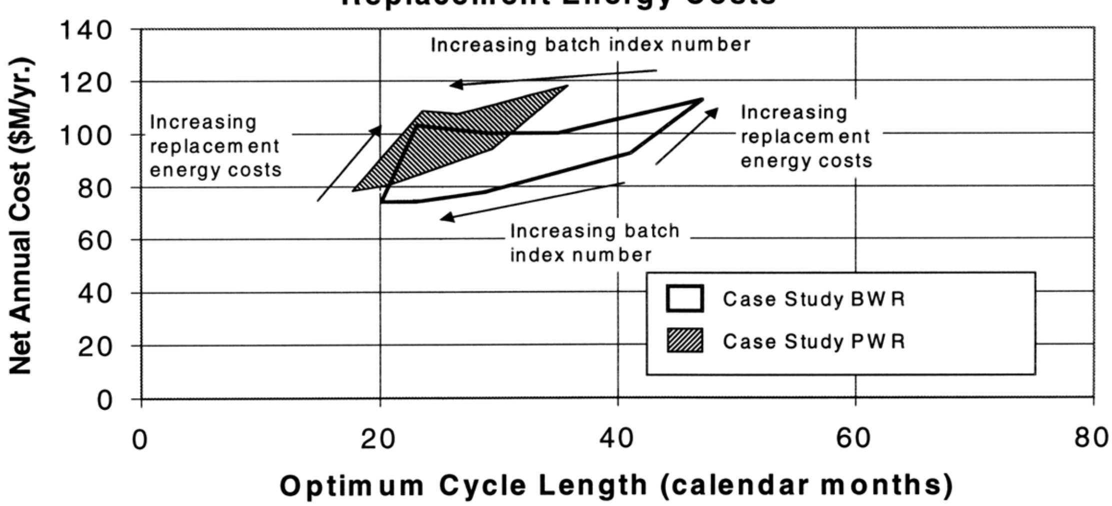


Figure 4-15: Effect of Replacement Energy Cost on Cost and Optimum Cycle Length for the Case Study PWR at n=3



As for the effect that replacement energy costs have on the optimum cycle length, it can be seen in Figure 4-13 that as replacement energy costs decrease, so does the optimum cycle length for n=1, on the order of 1.5 calendar months for every 10 mills/kwhre. For increasing n, this ratio holds relatively constant, suggesting that as the number of batches changes (for a fixed cycle length), the optimum cycle length is independent of the effects of varying replacement energy cost. It is important to note that current burnup limits prevent realization of the fullest economic potential, i.e. the optimum, as n increases. This is not as large of a problem for n = 2, where the cost at the optimum is comparable to the cost at the burnup limit, as it is for n=3, where the difference between the cost at the burnup limit and the optimum varies between 0 and ~$5M/yr. This suggests that increasing current burnup limits would be a way for multi-batch cores to become more competitive in a deregulated energy market. These effects are shown as replacement energy cost is varied for each n in Figures 4-13 through 4-15 for the case study PWR. The overall effect on optimum cycle length as replacement energy costs and n are varied for both the case study BWR and PWR is shown in Figure 4-16.

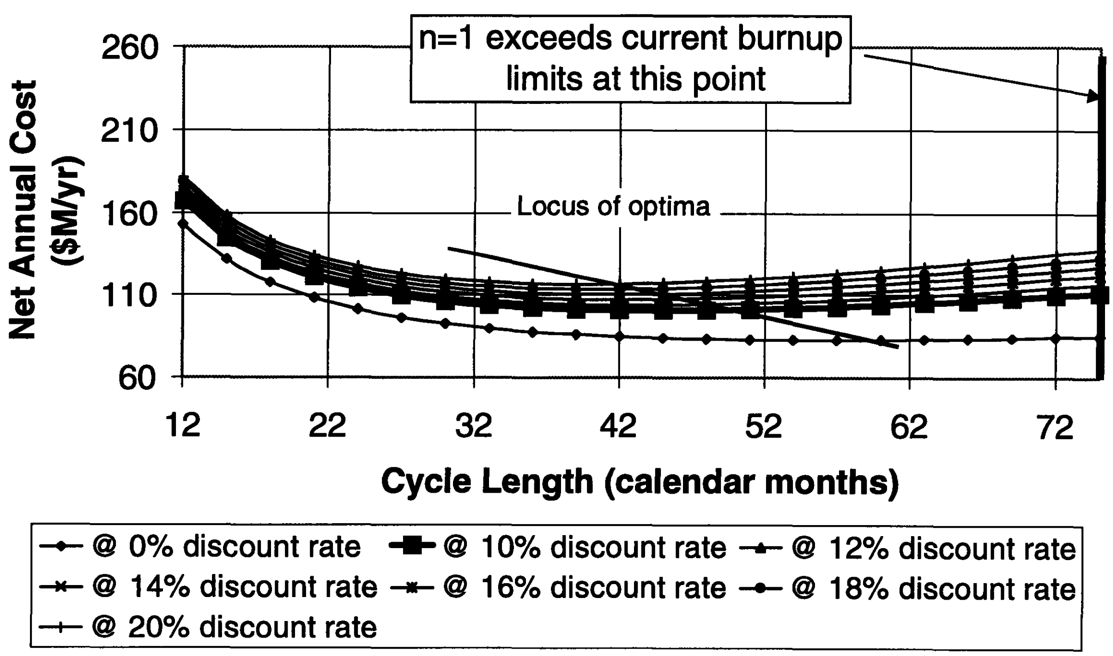
Figure 4-16: Optimum Regions for the Case Study Plants as a Function of Batch Index Number and Replacement Energy Costs



4.4.4.2 Carrying charge rate

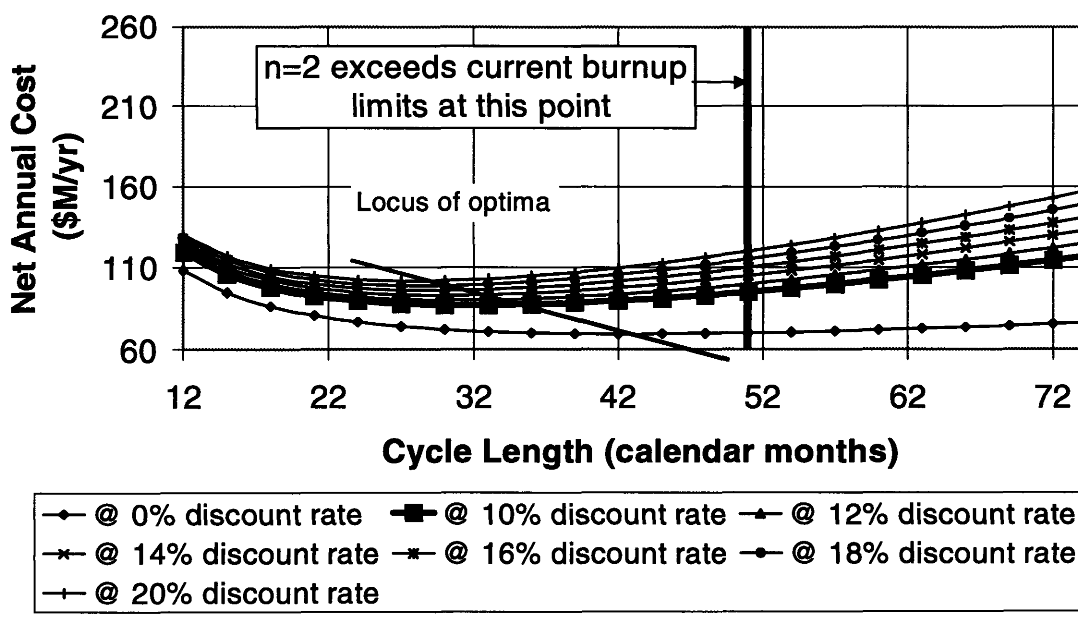
Another concern that arises because of a deregulated market is the effect of a change in the carrying charge rate that is used to finance fuel costs. Assessed at 10%/yr. in the base case, carrying charge rate is predicted to increase with deregulation, as there will be more risk in a purely competitive market. Looking first at the overall effect that carrying charge rate has on the case study BWR, Figure 4-17 shows, for the limiting case of a discount rate of 0, an increase in the optimum cycle length and a flattening of the cost curve around the optimum region. Because of this flattening of the cost curve at the optimum and for ultra-long cycle lengths, it is reasonable to conclude that there is really no economic limit to cycle length extension for very low financing costs. However, technical feasibility would dictate that a cycle length be chosen at the shorter end of the flat region of this curve, ~ 48 calendar months.

Figure 4-17: Effect of Discount Rate on Cost and Optimum Cycle Length for the Case Study BWR at n=1



Further study of Figure 4-17 shows that as carrying charge increases, optimum cycle length decreases only slightly, about 6 calendar months for every 10%/yr. However, as is the case with no discount rate, these optima are in a fairly flat region, and comparable costs are seen for a 6 month range around the optimum. The effect of the discount rate on net annual cost is also a direct one, as an increase in the discount rate leads to an increase in total costs, as expected. This increase, however, varies with cycle length with a \$1.4M/yr. increase per 1% increase in discount rate at 12 calendar months increasing to ~\$2.6M/yr. increase per 1% increase in discount rate at 75 calendar months over the range of cycle lengths. This suggests that the longer the cycle length, the greater the sensitivity to discount rate and hence, a de-regulated energy market. However, because the flat optima regions found for all curves lie near the same range of cycle lengths, the predictions for the optimum extended cycles are relatively insulated from the effects of a changing carrying charge rate.

Figure 4-18: Effect of Discount Rate on Cost and Optimum Cycle Length for the Case Study BWR at n=2



Figures 4-18 through 4-20 show the same effects for 2, 3, and 4-batch fuel management for the case study BWR. However, as n increases, the effect that a change in carrying charge rate has decreases, as was the case with the replacement energy parametric study. This supports the idea that a multi-batch fueling strategy may be better than a single batch loading to safeguard against the effects of market uncertainty. Additionally, it is interesting to note that the optima predicted for each strategy are not restricted by the prescribed burnup limits for all carrying charge rates, showing that extending these limits would not give any unique economic benefits to extended operating cycles in the case study BWR.

Figure 4-19: Effect of Discount Rate on Cost and Optimum Cycle Length for the Case Study BWR at n=3

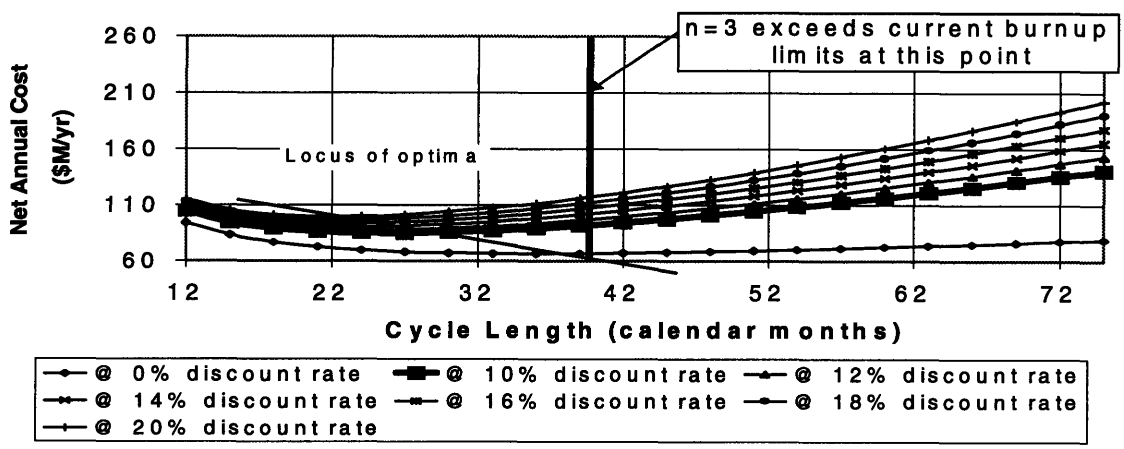
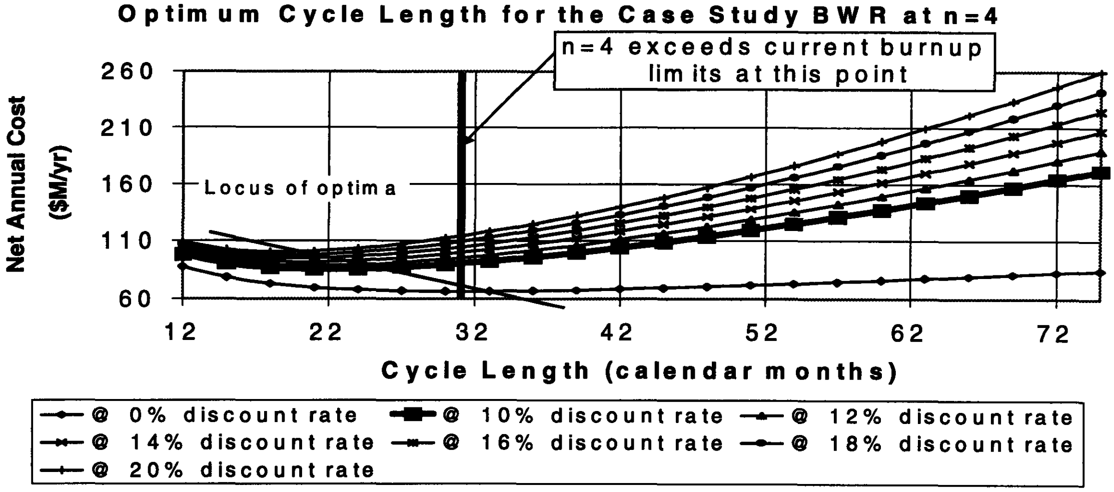
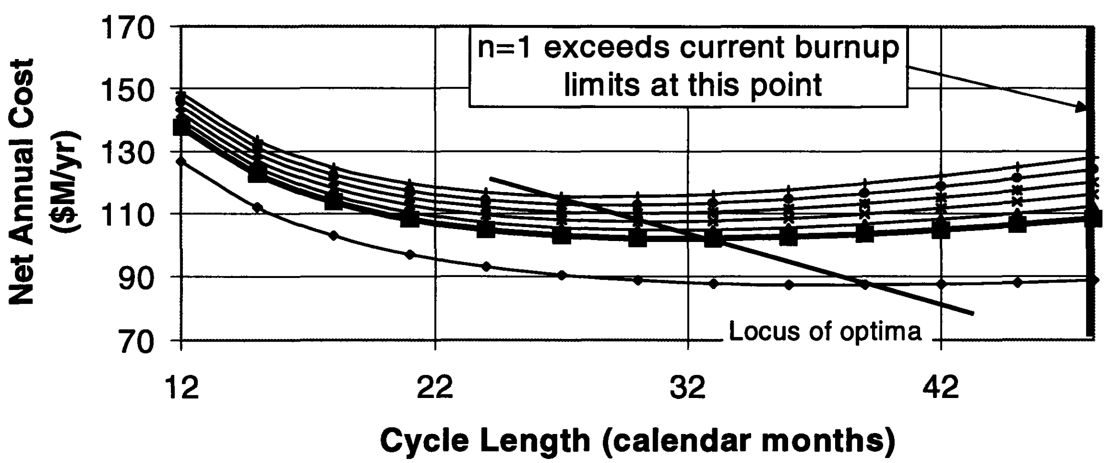


Figure 4-20: Effect of Discount Rate on Cost and Optimum Cycle Length for the Case Study BWR at n=4



Again, similar results can be seen for the case study PWR, in Figures 4-21 through 4-23. As discount rate increases, so does the net annual cost of implementing an operating cycle strategy. However, while this cost difference varies with cycle length, as it did with the case study BWR, the range of cost differences is greater for the case study PWR: $1.1M/yr. at 12 calendar months ($1.4M/yr. for the case study BWR) and $2.0M/yr at 48 calendar months (~$1.75M/yr. for the case study BWR at 48 calendar months). This phenomenon is due mainly to the fact that at the lower end of this range, the case study BWR has higher fuel costs (due to the net increase created by the competing effects of lower specific power, i.e. lower enrichment, and greater core load) and consequently a change in carrying charge rate will have a greater effect. At higher discount rates, the effect is greater for the PWR, as fuel costs are higher because the higher specific power dictates a greater incremental increase in enrichment-related fuel costs as cycle length is extended.

Figure 4-21: Effect of Discount Rate on Cost and Optimum Cycle Length for the Case Study PWR at n=1



@ 0% discount rate; @ 10% discount rate; @ 12% discount rate; @ 14% discount rate; @ 16% discount rate; @ 18% discount rate; @ 20% discount rate

Figure 4-22: Effect of Discount Rate on Cost and Optimum Cycle Length for the Case Study PWR at n=2

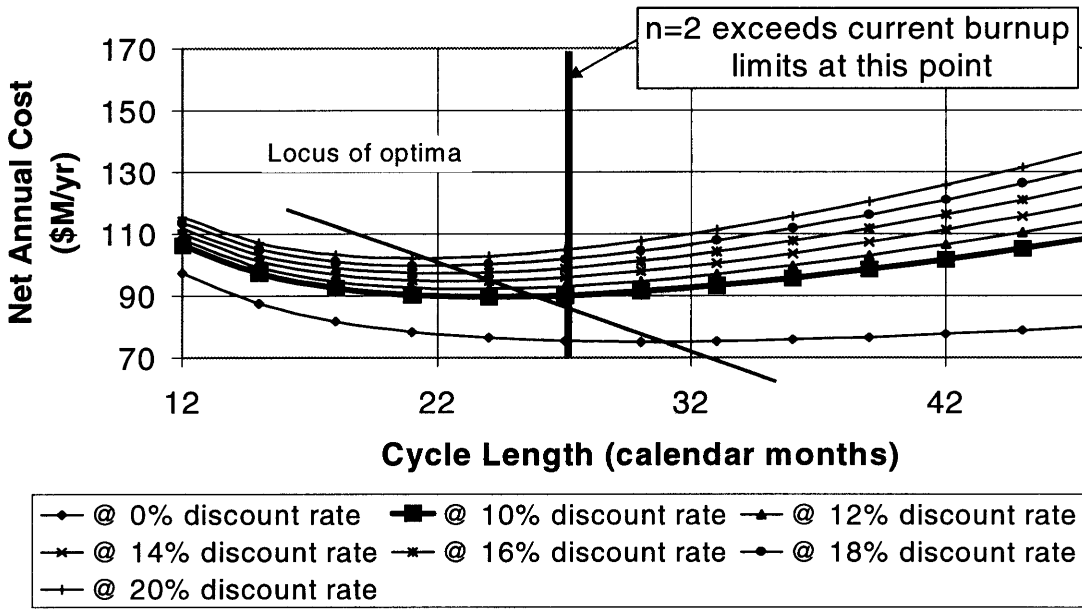
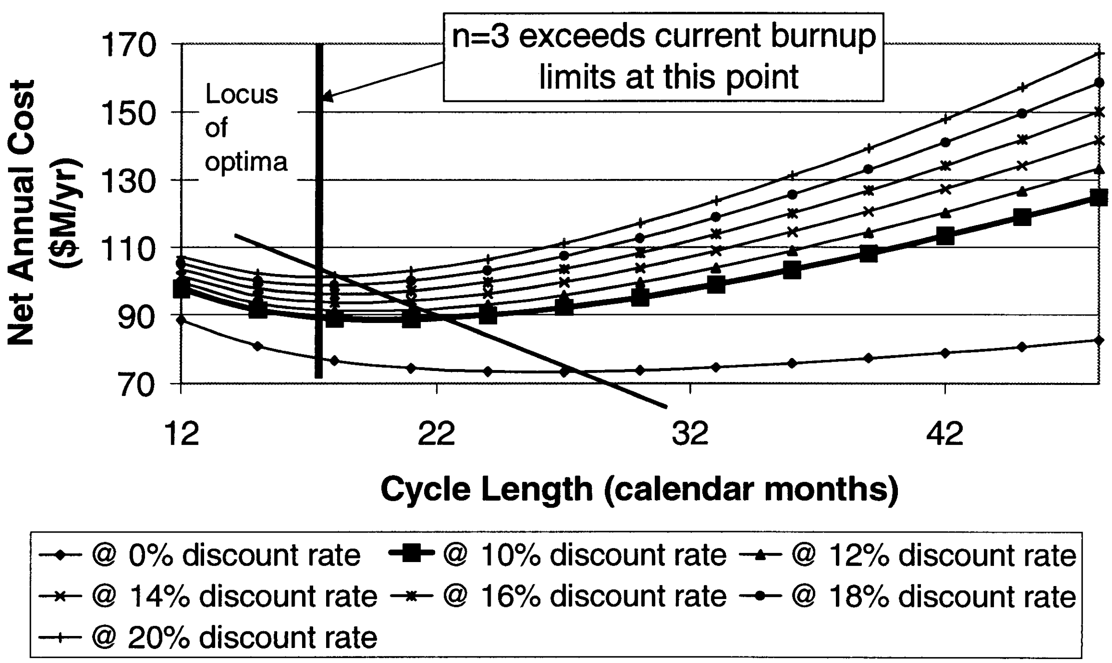


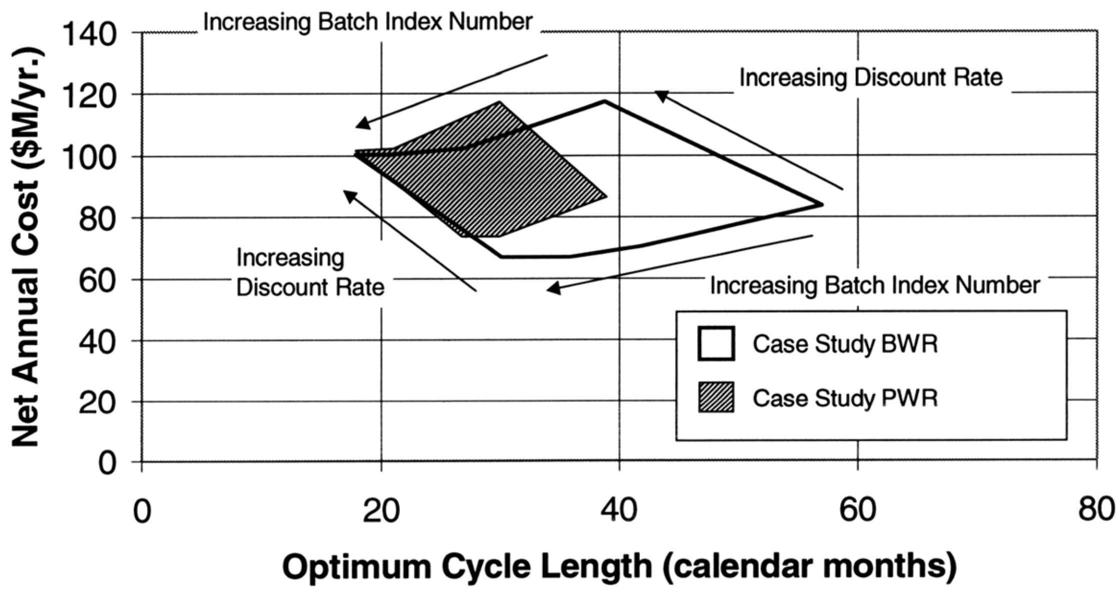
Figure 4-23: Effect of Discount Rate on Cost and Optimum Cycle Length for the Case Study PWR at n=3



Optimum cycle length also decreases as carrying charge rate increases. As n increases, the burnup limit gets closer to the optima, to the point that for n=3 (Figure 4-23) the optima all lie beyond the current burnup limit. Fortunately, the optima are found in a relatively flat region of the curve, just as with the BWR, and comparable benefits can be realized for discount rates greater than 10%/yr. while still respecting burnup limits. Another advantage that this flatness of the optimum region presents is that it keeps the optimum cycle length at relatively the same place regardless of the discount rate. This suggests that the location of the optimum cycle length is relatively independent of carrying charge rate, between 10 and 20%/year.

The overall effect on optimum cycle length as carrying charge rate and n are varied for both the case study BWR and PWR is shown in Figure 4-24.

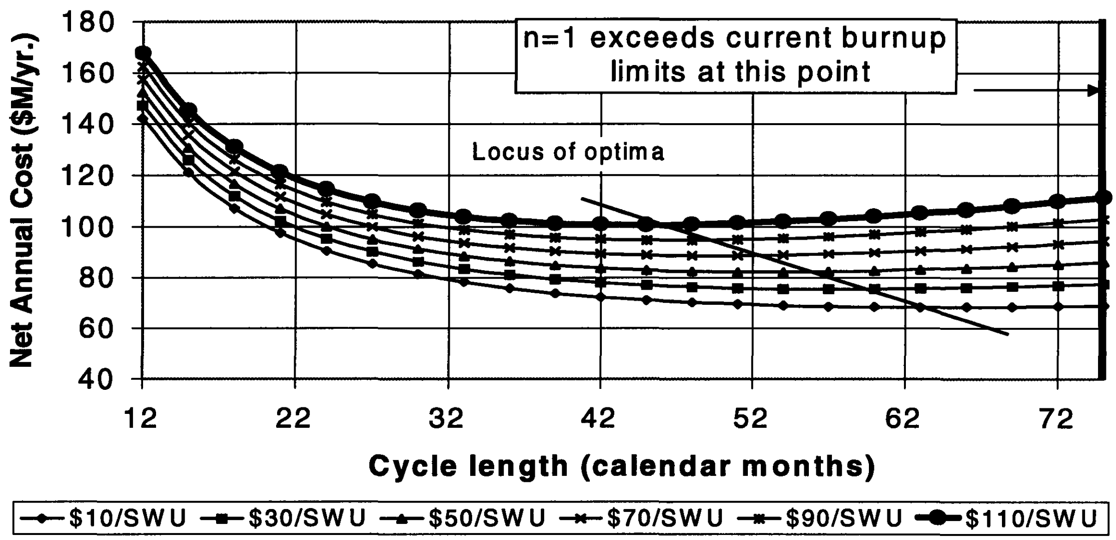
Figure 4-24: Optimum Regions for the Case Study Plants as a Function of Batch Index Number and Discount Rate



4.4.4.3 Innovations in enrichment technologies

Given that extended operating cycles incur much higher fuel costs due to their higher enrichments, lower unit enrichment costs due to technological innovation holds great promise for cutting extended cycle costs significantly, as shown in Section 4.3.1. Consequently, lower unit enrichment costs may have an effect on the optimum cycle length. Looking first at a single batch fueling strategy for the case study BWR in Figure 4-25, net annual cost decreases for a decrease in the unit cost of enrichment. This cost decrease is more significant for longer cycles, as there is more opportunity for savings with lower unit enrichment costs for those strategies which use higher enrichments. As the unit cost of SWU decreases, the optimum cycle length at which to operate increases, on the order of 18 calendar months for a $100 decrease in the unit cost of SWU. More importantly, the region around the optimum stays relatively flat as the unit cost of enrichment decreases, providing added operational flexibility for extended cycles, regardless of unit enrichment costs.

Figure 4-25: Effect of Enrichment Costs on Cost and Optimum Cycle Length for the Case Study BWR at n=1



Comparable results can be seen for multi-batch fuel management in Figures 4-26 through 4-28. As the unit cost of enrichment decreases, so does the cost associated with operating at these strategies. Again, as cycle length increases, so does the savings associated with a lower unit enrichment cost; however these savings become more pronounced as n increases. This can be explained by the fact that as n increases for a given cycle length, more life (burnup) is extracted from the core, requiring a higher enrichment. The effect of the region around the optimum becoming flatter with a decreased unit SWU cost occurs for 2, 3, and 4 batch management and further supports the inherent operational flexibility of operating around the predicted economic optimum for lower unit enrichment costs. Should these lower SWU costs be realized, the inherent flatness of the curve would provide additional insurance against the possibility of an incorrect prediction of optimum extended cycle length.

Figure 4-26: Effect of Enrichment Costs on Cost and Optimum Cycle Length for the Case Study BWR at n=2

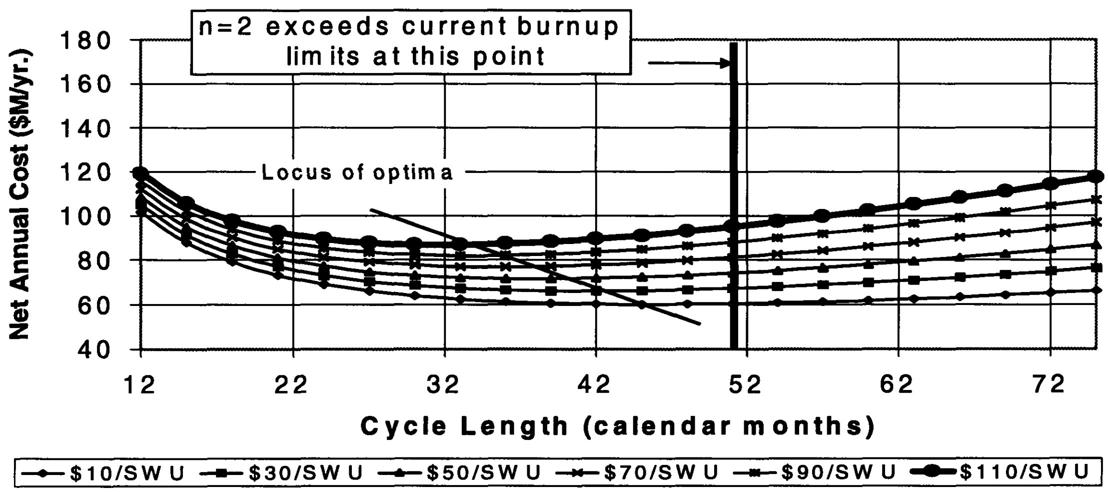


Figure 4-27: Effect of Enrichment Costs on Cost and Optimum Cycle Length for the Case Study BWR at n=3

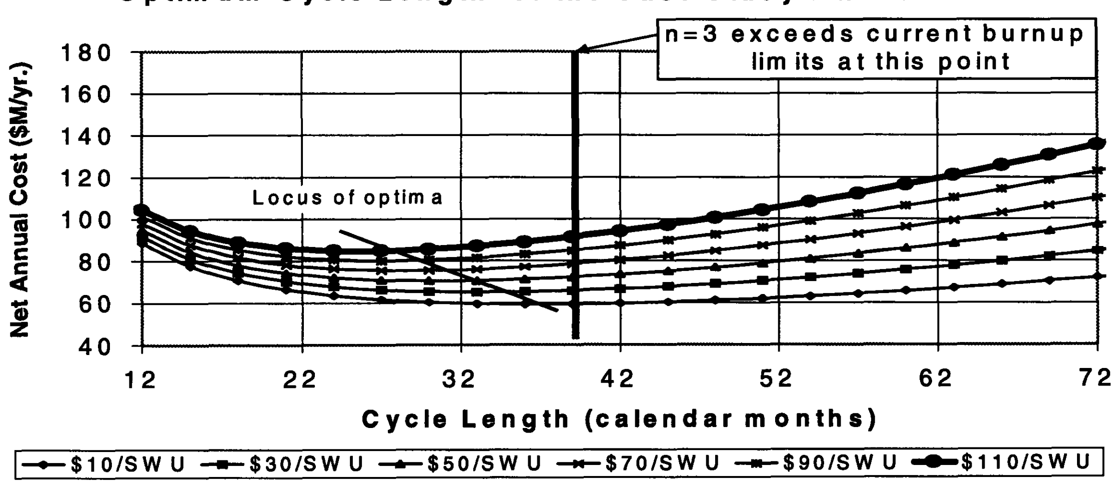
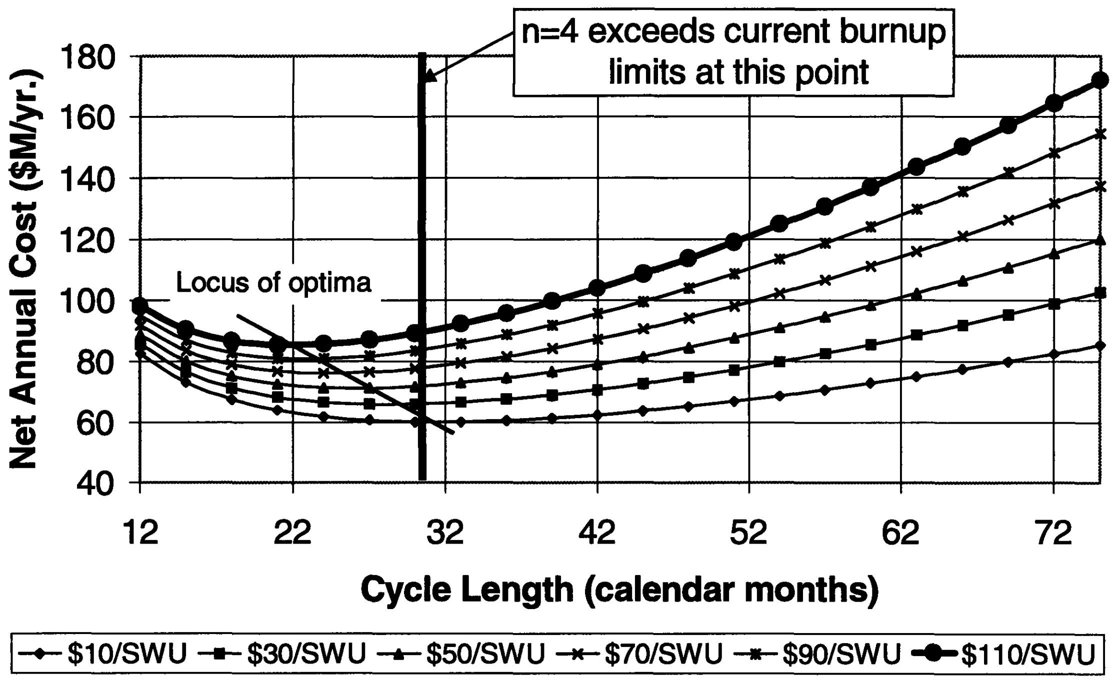


Figure 4-28: Effect of Enrichment Costs on Cost and Optimum Cycle Length for the Case Study BWR at n=4



Calling attention to the burnup limits shown in Figures 4-26 through 4-28, the plots show that as unit enrichment costs decrease, the optimum cycle length gets closer to these limits. However, the optimum cycle length (or a cycle length with comparable benefits) does not exceed these limits, regardless of SWU costs. Therefore, burnup limits will not constrain the economic potential associated with the implementation of lower unit enrichment costs in the case study BWR.

For the case study PWR, the same results are found for the same reasons except for the results related to the burnup constraints. For single batch fuel management, shown in Figure 4-29, all of the optima for different SWU costs are within current burnup limits. However, as n increases for a given cycle length, the optimum cycle length gets closer to and even exceeds the burnup limit (in some cases, especially for n=3), as shown in Figures 4-30 and 4-31.

Figure 4-29: Effect of Enrichment Costs on Cost and Optimum Cycle Length for the Case Study PWR at n=1

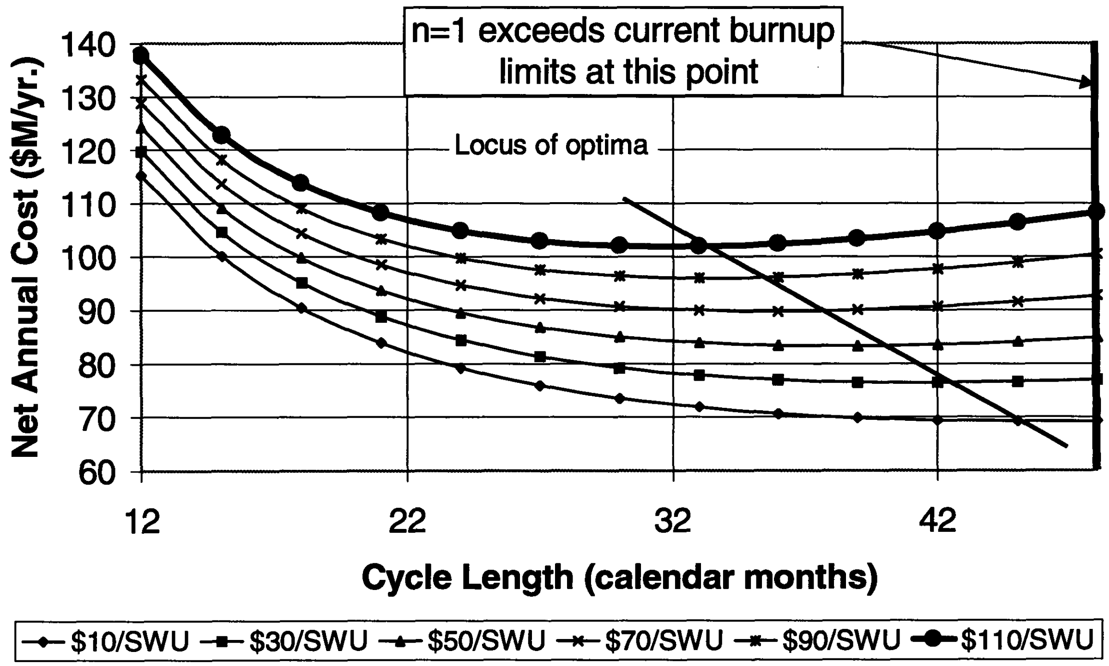


Figure 4-30: Effect of Enrichment Costs on Cost and Optimum Cycle Length for the Case Study PWR at n=2

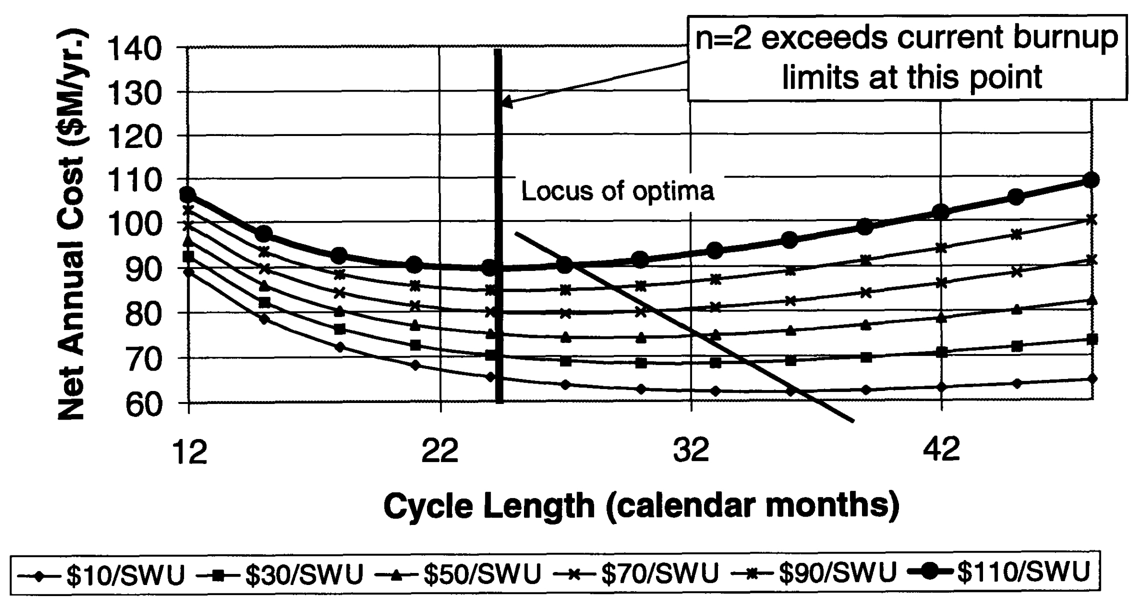
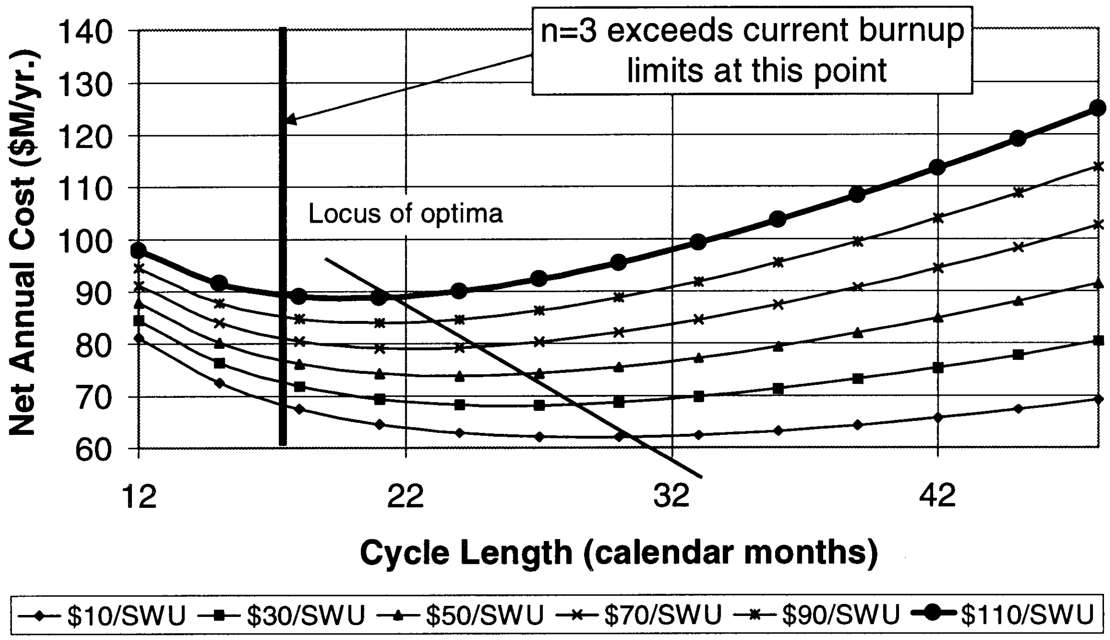


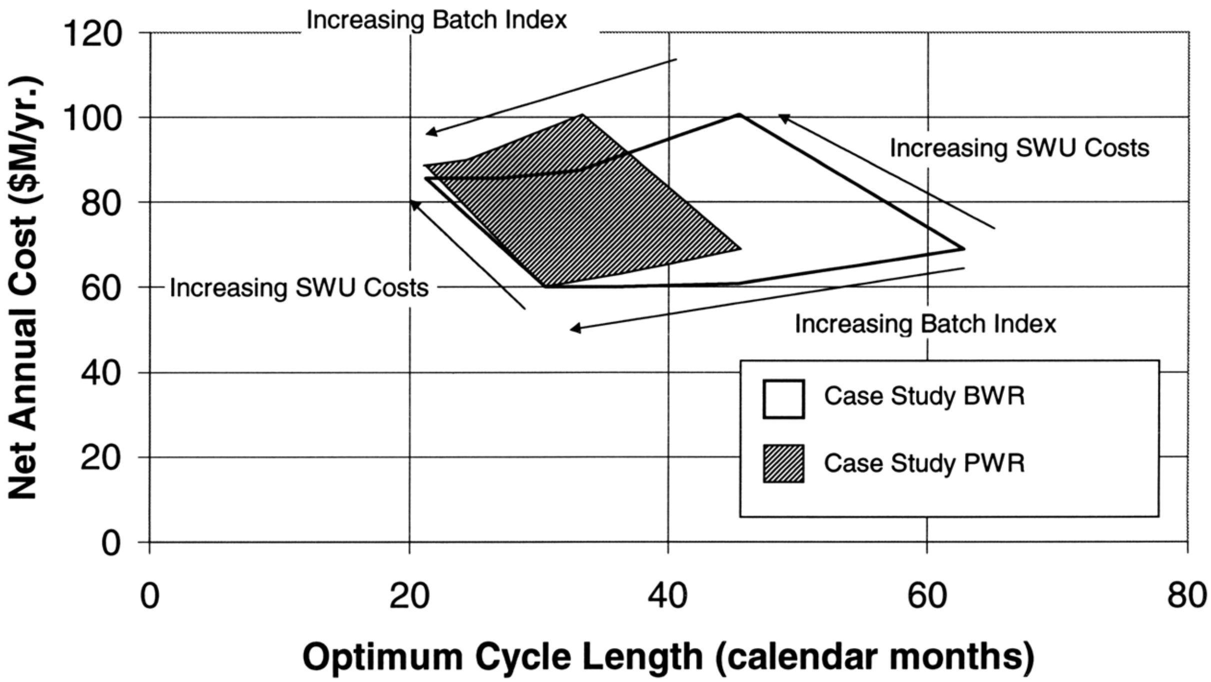
Figure 4-31: Effect of Enrichment Costs on Cost and Optimum Cycle Length for the Case Study PWR at n=3



The difference between the cost of the cycle length at the burnup limit and the optimum cycle length ranges from $1M/yr. at $50/SWU to $3M/yr. at $10/SWU for n=2 and $0.5M/yr. at $110/SWU to $6M/yr. at $10/SWU. This suggests that the full economic potential of lower unit enrichment costs for optimizing extended operating cycles could not be realized because of current burnup limits. This presents an inherent disadvantage for multi-batch, extended operating cycles in the case study PWR, given advances in enrichment technology, and motivates R&D to increase fuel burnup capability.

The overall effect on optimum cycle length as enrichment costs and n are varied for both the case study BWR and PWR is shown in Figure 4-32.

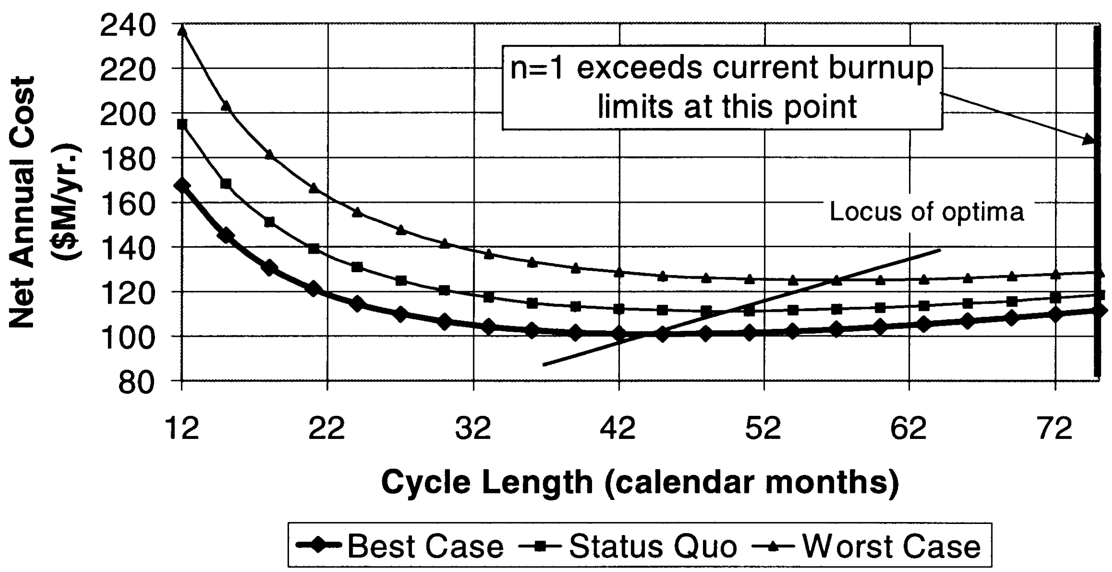
Figure 4-32: Optimum Regions for the Case Study Plants as a Function of Batch Index Number and Enrichment Costs



4.4.4.4 Operational parameters

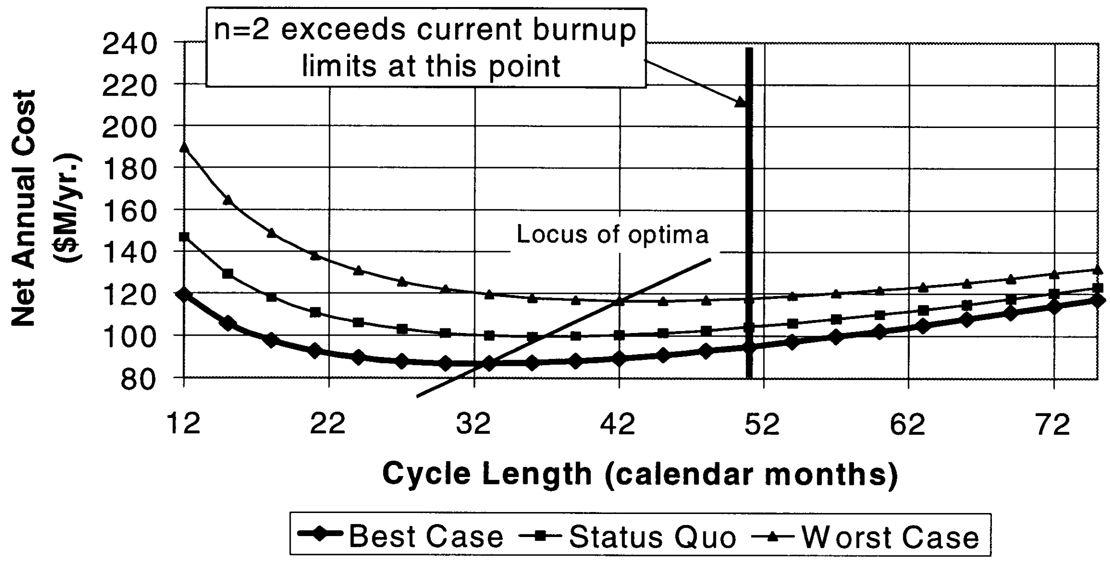
While the predictions made for the parameters (RFO, FOR) used in the previous four sections were based on how a good performing plant would be affected by cycle length extension, how extended operating cycles would affect plants with less than optimal performance is also important. Further, while these predictions of operating parameters can be considered valid, the inevitability that these predictions will be wrong requires that a look be taken at the sensitivity of the results to these parameters. Holding cycle length fixed, the "best-case" scenario, i.e. RFO and FOR held constant at 30 days and 3%, respectively, will be compared to a "status quo" case, (RFO = 49 days, FOR=6%), and a "worst case" scenario (RFO = 80 days, FOR = 10%) to show how extending cycle length would affect plants having a range of performance attributes.

Figure 4-33: Effect of Operational Parameters on Cost and Optimum Cycle Length for the Case Study BWR at n=1



Looking first at Figure 4-33 for single batch fuel management, as operational parameters get worse, the cost of operating the case study BWR increases. While this last observation is intuitively obvious, this figure also shows that as cycle length increases, the change in cost with respect to the worsening operational conditions decreases. Further, the optimum cycle length increases by approximately six months as the operating conditions worsen in each of these scenarios. Once again, however, these optima are in relatively flat regions of the curve, lessening the impact of a change in cycle length around the optimum. These last two observations are important to understanding the economic effects of extended operating cycles as they show that the longer the cycle length, the less sensitive the costs are to the RFO and FOR, hence, capacity factor.

Figure 4-34: Effect of Operational Parameters on Cost and Optimum Cycle Length for the Case Study BWR at n=2



Figures 4-34 through 4-36 show what happens to these cost curves as n increases. While the cost curves for each batch fraction have the same difference in cost between themselves at smaller cycle lengths, this difference decreases for increasing cycle lengths. At a given cycle length, this difference also decreases as n increases, to the point that all of the cost curves nearly converge at 75 calendar months for n=4. These two effects suggest that extending operating cycle length insulates cost (to an extent) from the effect of uncertain or varying operational parameters, especially as n increases.

Also, given the comparatively steeper part of the curve at shorter cycle lengths for the worst case scenario, a greater margin of savings could be achieved by poorer performing plants with cycle length extension than with the "best case" scenario. Obviously, the best case plants are much more economically attractive; however, from the results in Figures 4-33 through 4-36, there is more of an opportunity for poorer performing plants to cut costs with extended operating cycles than for plants that run well. It should be noted that although plants which are the "poor" performers have much more to gain from cycle length extension, they are perhaps the least likely to do so, given the difficulties that they face with current practice.

Figure 4-35: Effect of Operational Parameters on Cost and Optimum Cycle Length for the Case Study BWR at n=3

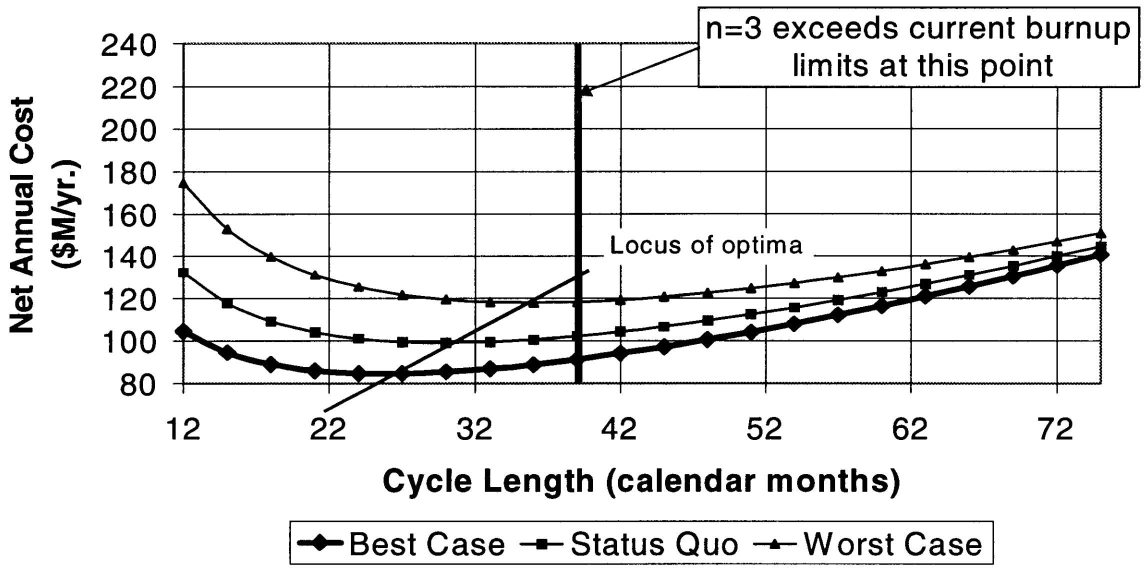
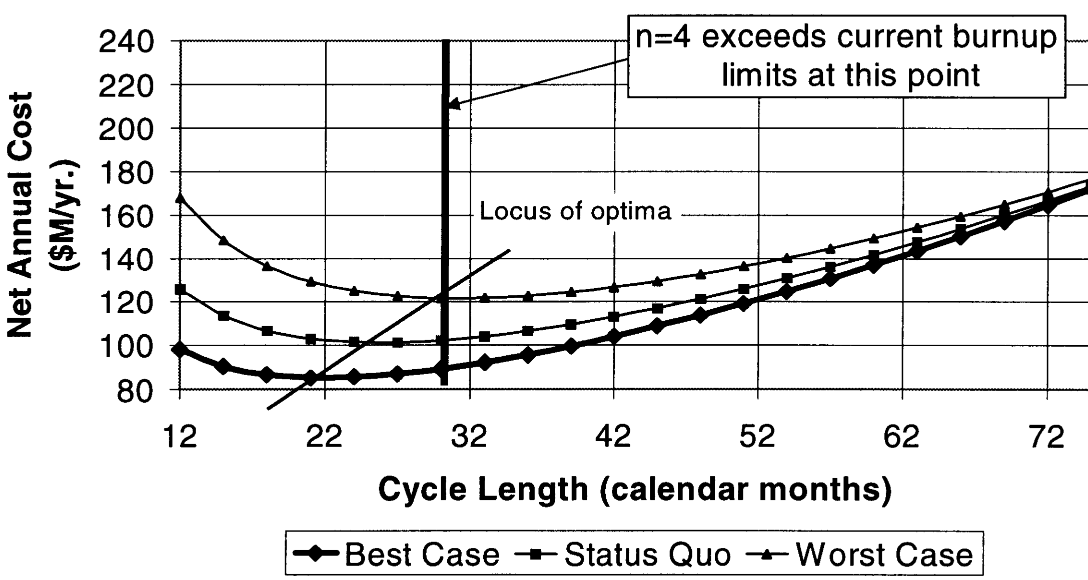
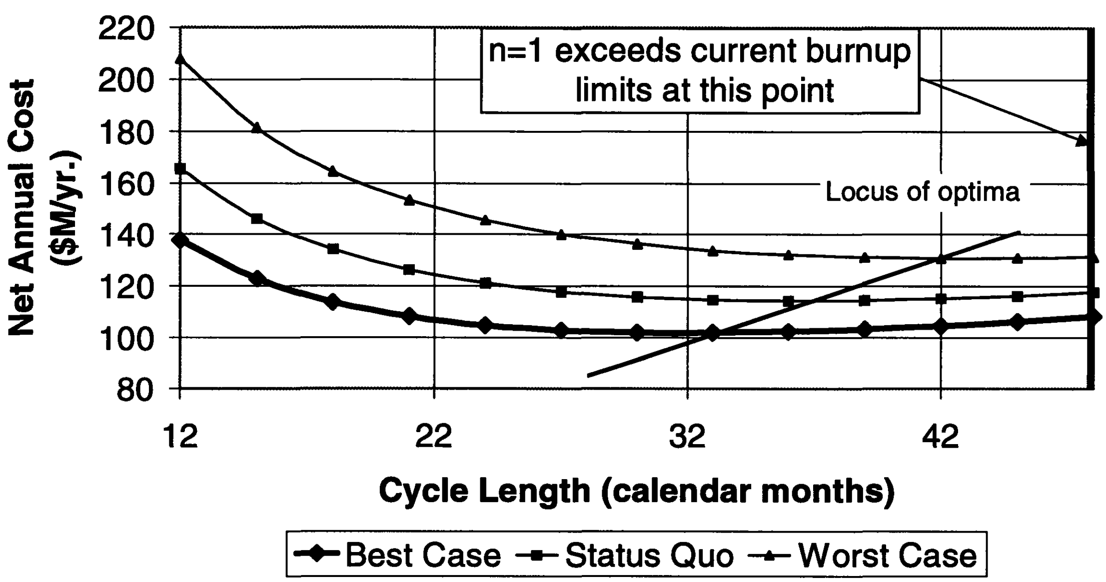


Figure 4-36: Effect of Operational Parameters on Cost and Optimum Cycle Length for the Case Study BWR at n=4



Turning attention to how the optima vary with operational parameters for multi-batch fuel loading, results similar to those found for n=1 are found. As n increases, the amount by which the optimum cycle length changes (increases) with worsening operational parameters remains relatively constant, about 4.5 months for each scenario, compared to 6 months for a single batch fueling strategy. It is also of interest to note that the optima are at or near the current burnup limits in these figures. Thus, increasing current burnup limits holds no economic incentive from the perspective of plant operations for the case study BWR.

Figure 4-37: Effect of Operational Parameters on Cost and Optimum Cycle Length for the Case Study PWR at n=1



Considering next the case study PWR in Figures 4-37 through 4-39, similar effects as for the case study BWR are observed as operational parameters are varied. For all three fuel management strategies, as cycle length increases the cost difference between plants with different operational characteristics decreases. Again, for a fixed cycle length, the cost difference between scenarios decreases as n increases. Additionally, the slope of the "worst case" cost curves is steeper at shorter cycle lengths than the cost curves for the "status quo" or "worst case" scenarios, suggesting that there is a greater margin of savings available for poorer performing plants by extending cycle length.

Figure 4-38: Effect of Operational Parameters on Cost and Optimum Cycle Length for the Case Study PWR at n=2

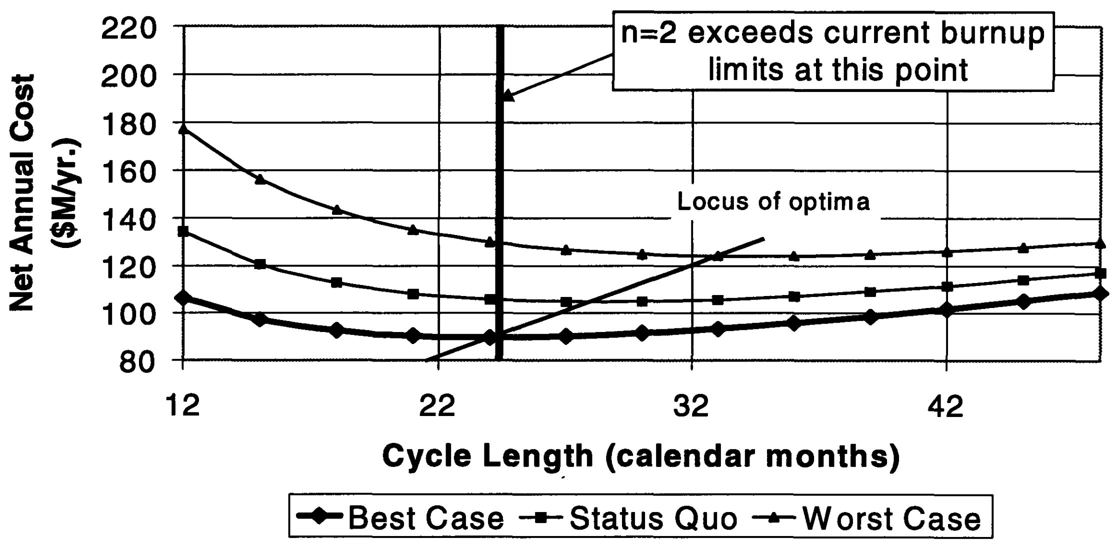
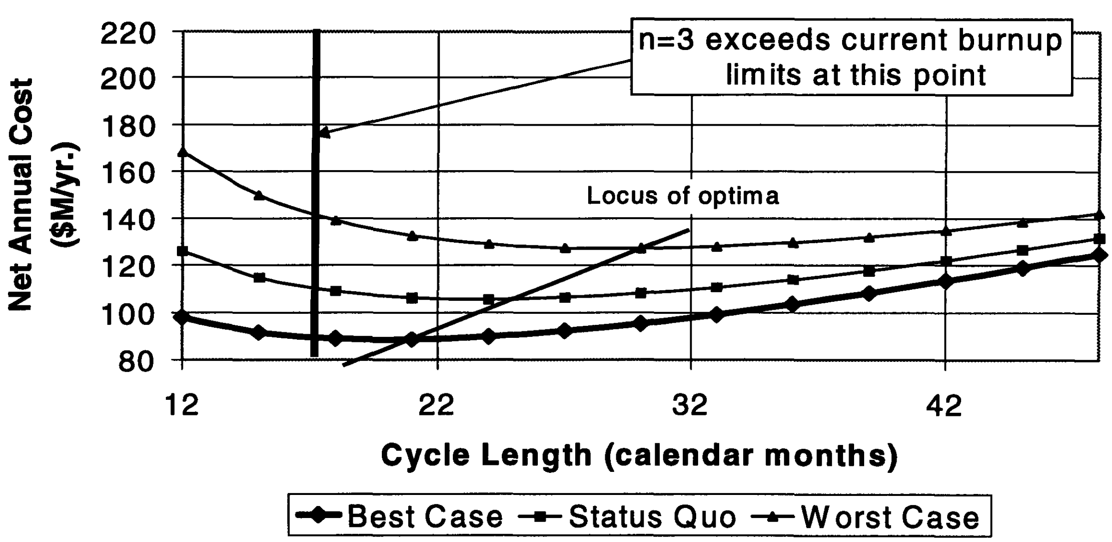


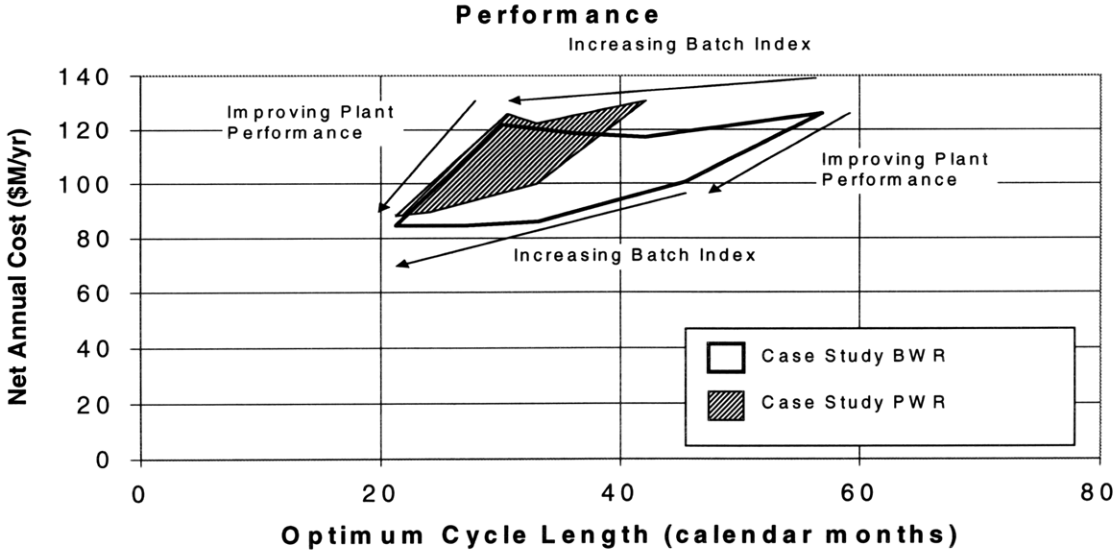
Figure 4-39: Effect of Operational Parameters on Cost and Optimum Cycle Length for the Case Study PWR at n=3



While many of the results of the case study BWR and PWR with respect to changing operational parameters are the same, burnup limits are much more constraining for multi-batch fuel loading in the PWR. With respect to the effect that poorer operating conditions have on the optimum cycle length, Figures 4-37 through 4-39 show that the optimum increases consistently by 3 calendar months for the "status quo case" and 9 calendar months for the "worst case" as compared to the "best case" scenario.

While burnup limits do not present a barrier to achieving these optima for single batch fuel management, these limits present large opportunity losses for n=2 and n=3. Specifically, the difference between the cost at the burnup limit and the cost at the optima range from 0 to $6M/yr. for n=2 and ~$0.3M/yr to $13M/yr. for n=3 depending upon the scenario. This suggests that there is an economic incentive for increasing these burnup limits for the case study PWR, since not all plants will operate under the best case conditions. Additionally, increasing these burnup limits would allow for longer cycle length operation of multi-batch fueling strategies, minimizing the amount of spent fuel generated per annum.

Figure 4-40: Optimum Regions for the Case Study Plants as a Function of Batch Index Number and Plant Performance



The overall effect on optimum cycle length as plant performance and n are varied for both the case study BWR and PWR is shown in Figure 4-40.

4.5 Conclusions

An economic model has been developed for assessing the economics of extending operating cycles in existing LWRs. While cases at the limits of technical feasibility and at what is predicted to be near the economic optimum have been examined for the case study BWR and PWR, these cases have shown that the extent of the economic viability of extending operating cycle length is dependent upon the operational parameters chosen to represent the different cycles being compared. For the specified parameters chosen, the extended cycle chosen for the case study BWR and PWR is shown to be **~\$8.9M/yr.** more expensive and **~\$1.0M/yr.** more attractive than the corresponding reference cases, respectively.

Additionally, the economic model was used in conjunction with a burnup-enrichment correlation to predict the economically optimum cycle length at which to operate. Results showed that for the case study BWR and PWR parameters, these optima were within or near current burnup limits and that multi-batch fuel management was always more economically attractive than a batch reload strategy. Given that cycle length was varied over a wide range and the operating parameters (RFO, FOR) that were chosen to approximate plant best practice were held constant over this range, the results from this cycle length optimization suggest that it is more economically sound to invest in improving current operations than to invest in extended operating cycles. The parametric studies that were performed suggest that removing burnup limits would help the full economic potential of extended operating cycles be realized in the case study PWR, given uncertainty in future market and operating conditions. Overall, cheaper unit enrichment costs appear to be the most feasible prospect for making extended operating cycles more attractive.

CHAPTER 5: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary and conclusions

An evaluation of all of the obvious economic factors that would be involved in implementing an extended operating cycle has been made. These factors were organized in two main categories: fuel cycle economic factors and operations and maintenance (O&M) economic factors. From this breakdown, it was determined that because such large additional costs were associated with the fuel cycle considerations, large compensatory savings would need to be realized from the (O&M) factors for this project to be successful. The economic factors examined in this paper are summarized in Tables 2-5, Summary of Fuel Cycle Economic Factors, and 3-4, Summary of O&M Economic Factors. The cost differences in these tables are those between the projected extended cycle batch loaded core and current practice, having the operating and plant parameters outlined in Table 1-1 and the economic characteristics defined in Appendix D.

With respect to fuel cycle economic considerations, the extra costs that would be incurred from implementing an extended cycle would stem from the increased enrichment necessary to maintain criticality for the life of the core. The largest of these expenditures, the cost of the fuel, was estimated to increase by ~$33.9 M/yr. and ~$33.1M/yr. for the case study BWR and PWR, as shown in Table 2-1.

Although various ways to reduce the annual fuel cost increase endemic to extended operating cycles were considered, only one solution, the Radial Blanket Assembly (RBA) fueling scheme (which uses lower enriched fuel in the peripheral assemblies for fuel cost savings, neutron economy, and vessel fluence reduction), was found to have a substantial impact and to be technically feasible for all lengths of cycle extension.

Other reductions were found to be relatively minimal, and in some cases, were offset by increases in other areas. Thus, it is this large fuel cost increase that presents the greatest barrier to the project's economic viability. Parametric studies showed that a significant decrease in unit enrichment costs would favor long-cycle operations more than any other likely development (see Table 5-1).

Table 5-1: Summary of Parametric Studies

Study		BWR Effect	PWR Effect
Figure 2-3	Economic Effect of Enrichment	\$1.6M/yr. savings per 0.1 $^{w}/_{o}$ U-235	\$1.2M/yr. savings per 0.1 $^{w}/_{o}$ U-235
Figure 2-4	Discounted Fuel Cost as a Function of Fabrication Penalty	\$0.12M/yr. cost increase per 1% fabrication penalty	\$0.09M/yr. cost increase per 1% fabrication penalty
Figures 2-7 and 2-8	Effect of New Enrichment Technologies on Fuel Costs	\$8M/yr. decrease in fuel cost increase for SWU costs cut in half	\$10M/yr. decrease in fuel cost increase for SWU costs cut in half
Extended and Reference Cycle Parametric Studies			
Figures 4-2 and 4-3	Costs for the Case Study LWRs as a Function of Operational Parameters	Extended cycles become more attractive as RFO increases and as the difference in FOR increases , in favor of extended cycles	
Figure 4-4	Effect of Innovations in Enrichment Technologies on the Case Study LWRs	Break Even SWU cost for extended cycle viability = \$49.50/SWU	Break Even SWU cost for extended cycle viability > \$110/SWU
Case Study Parametric Studies (RFO=30 d, FOR=3%)			
Figures 4-9 Through 4-15	Effect of Replacement Energy Cost on Net Annual Cost and Optimum Cycle Length for the Case Study LWRs at Different n	As replacement energy costs increase, so do both the net annual cost and the optimum cycle length; effects relatively independent of n	

Figures 4-17 through 4-23	Effect of Carrying Charge Rate on Net Annual Cost and Optimum Cycle Length for the Case Study LWRs at Different n	As carrying charge rate increases, the net annual cost increases and the optimum cycle length decreases; as n increases, the magnitude of these two effects decreases
Figures 4-25 through 4-31	Effect of Enrichment Cost on Net Annual Cost and Optimum Cycle Length for the Case Study LWRs at Different n	As unit enrichment costs decrease, the net annual cost decreases and the optimum cycle length increases; net annual cost decreases with n; optimum cycle length effect relatively constant over different n
Case Study Parametric Study (RFO and FOR varied)		
Figures 4-33 through 4-39	Effect of Operational Parameters (RFO, FOR) on Net Annual Cost and Optimum Cycle Length for the Case Study LWRs at Different n	As operational parameters worsen, net annual cost increases and optimum cycle length increases; increase in net annual cost lessens as cycle length increases to the point that these costs converge at ultra-long cycle lengths; as n increases, this convergence happens at a shorter cycle length; relationship between optimum cycle length and operational parameters is relatively independent of n.

Aside from the obvious benefit of increasing revenue due to increased power production, several other O&M economic advantages were considered. Gains due to avoided refueling outages and less down-time were unique to an extended cycle, while an improved surveillance strategy, bolstered mainly by increasing the number of on-line and reduced power surveillances, could be used with any refueling strategy to improve plant performance. Despite the numerous O&M savings that could be realized with an extended cycle, there were also some costs associated with the new operating scheme that could negate part of these savings: in particular, the cost of transition to a batch reloaded core could be considerable because of the under-burned fuel thrown away.

While reasonably reliable dollar values could be associated with most of the fuel cycle costs, many of the O&M factors were much less accurately quantifiable. These items, indicated with a value of "UND" for undetermined in Tables 2-5 and 3-4, will only become more precise as a plant implementing an extended cycle strategy gets closer to fruition.

Looking at all of the different fuel management strategies for the case study BWR and PWR, it was found that multi-batch fueling is more economical than single batch fueling for cycle lengths not in the ultra-long range, i.e. less than 63 calendar months for the BWR and 48 calendar months for the PWR. Specifically, the fueling strategies that were found to be the most economically attractive under the current economic environment were found to be consistent with current practice: n=3, 24 calendar month cycle for the case study BWR and n = 2, 24 calendar month cycle for the case study PWR. Since these current practice cases were found to be optimal when compared to extended operating cycles when both were assessed the same operational advantages, i.e. RFO = 30 days, FOR = 3%, investing in improving current plant operations is clearly a more economically attractive option than cycle length extension, unless it can be shown that there are significant inherent incremental reductions in FOR and RFO length for the longer cycles.

The optima found for all batch indices in the case study BWR and PWR were not constrained by current burnup limits. However, the parametric studies performed in this report suggest that there is an economic incentive to increasing these burnup limits, especially for the case study PWR.

5.2 Recommendations for future work

Since many economic factors could only be broadly defined, there is considerable need for future work in this area. Of paramount concern is comprehensively defining all of the remaining factors associated with this new refueling scheme and attaching a dollar value to each, i.e. those factors listed with a cost of UND in Tables 2-5 and 3-4. While some factors may ultimately remain intangible or only bracketed by a range of estimates, this work will better help determine the benefit of extending cycle length and also lead to more clearly defined optimum cycle lengths.

The economic predictions made in this report have highlighted where some of the barriers to implementing extended operating cycles may lie. Inherent with a batch loaded, extended cycle operating strategy is the generation of more spent nuclear fuel, a large concern as spent fuel pools and temporary storage facilities fill up. While increasing the number of batches would help to mitigate this effect, multi-batch extended cycles run into the problem of violating current burnup limits. Given this concern over spent fuel and the potential economic benefits that could be gained from multi-batch extended cycle operation in an uncertain market (discussed earlier), research should be done to look at extending these burnup limits. Further, investigations into improving enrichment technologies to the point that these multi-batch extended cycles could be economically competitive with current practice is a key component to making a spent fuel minimization strategy work. As also noted earlier, lower SWU costs make batch reloading (n=1) more competitive. Finally, a minimum cost transition cycle from current multi-batch fuel management to single-batch management must be developed if ultra-long cycles are to be given further consideration.

CHAPTER 6: POLICY IMPLICATIONS OF EXTENDED OPERATING CYCLES

6.1 Introduction

While a comprehensive economic and technical evaluation of extended operating cycles has been made both here and elsewhere, the broader policy implications of this new operating strategy must also be assessed to accurately and comprehensively assess the feasibility of such an approach. The economic analysis and current state of US energy policy together point to three main policy issues as the most important factors in the success of such a strategy: (1) nuclear waste management, (2) development of advanced uranium separation technologies, and (3) the effects of a deregulated energy market. While the first two issues pose political and economic impediments to implementation of extended operating cycles, the third issue will have more of an effect once extended cycles are put into practice. While all three issues have ramifications for the nuclear power industry far and beyond their effects on extended operating cycles, how they affect this new operating strategy and its contribution to nuclear power longevity will be the focus of this chapter.

Implementing extended operating cycles successfully, i.e. cost-effectively, in existing LWRs in the US is one approach to promoting the longevity of nuclear power by warding off the threat of premature shutdown and by increasing incentives for plant life extension. This longevity is an important part of US energy policy over the next few decades, specifically with respect to energy security and the mitigation of the effects of global warming from Green House Gases (GHGs). An extra economic benefit of this longevity, allowing nuclear power plants to defer decommissioning costs and to collect more funds for these costs, further increases the viability of nuclear power as an energy generation technology.

Central to how extended cycles could contribute significantly to energy security and mitigation of global warming is the inherent operational benefit that is hypothesized to exist with such a strategy. Better performing, i.e. high capacity factor, plants are more economical, and thus secure the place of nuclear power in our nation's energy generation mix. This security provides for continued use of nuclear power plants, whose market for fuel is relatively insulated from global political volatility. This insulation is derived from the size of the domestic reserves of uranium and the dominance of US-based companies, such as the United States Enrichment Corporation (USEC), in the uranium enrichment market. Furthermore, the predominance of stable allies in the uranium market - Canada and Australia - is in sharp contrast to the situation with oil which has proven to be disruptive to our nations' energy needs in time of foreign political turmoil. Additionally, better performing plants produce more electricity, which eliminates the need to build as many fossil-fueled generating units to meet increasing energy demand. This avoided use of GHG-producing energy sources is a key benefit that extended operating cycles provide with respect to mitigating the harmful effects of global warming. Since coal is the principal competing energy generation technology to nuclear, the reduction in NO_x, SO_x, and particulates is also a considerable benefit.

This chapter will analyze the history and current status of the three main policy topics that have been identified as key issues with respect to implementation and operation of extended operating cycles. Solutions to help resolve the two issues that pose impediments will be offered and how a deregulated electricity market will affect extended operating cycles will be explored, given the constraints of the current and projected US political and economic climate. Further, how these three issues act as the cornerstones for a strategy which promises to bolster the longevity of nuclear power as a viable alternative in our nation's energy generation mix will also be explored.

6.2 Spent fuel minimization

Cited as a shortcoming of the commercial nuclear power industry since its inception, the disposal of spent nuclear fuel (SNF) will pose serious problems for the implementation of ultra-long operating cycles, given that this operating strategy has the inherent disadvantage of creating significantly more SNF than current practice (discussed in Section 2.2.2.1.2). Resistance to the increased generation of SNF rests with all parties involved in the issue: US Department of Energy (DOE), which is responsible for the long-term disposal of the SNF; nuclear utilities, which must store SNF until it can be disposed of; ratepayers, who bear the full cost of disposal; and environmental advocacy groups, who generally oppose any generation of environmentally unfriendly waste. It is because of this broadly based, opposing position that this issue poses such a large impediment to extended cycles.

The problem of SNF and more generally, High Level Waste (HLW), was first explored in 1955, when the National Academy of Sciences (NAS) was asked to recommend a strategy for the disposal of liquid chemically hazardous radioactive wastes resulting from the reprocessing of SNF. Suggesting that salt formations be used for disposal because of their geologic stability and isolation from water, the NAS study spurred the US to look at other subterranean strata for the disposal of SNF and HLW because of their analogous characteristics. Subsequently, the US began a program to nationally screen sites for HLW disposal that would take advantage of the natural barriers for long term waste isolation: aridity of the site, a deep-water table, slow-moving groundwater, and tectonic and seismic stability.

The first legislative action that helped move toward a solution on this issue was the Nuclear Waste Policy Act (NWPA) of 1982, which assigned the US DOE responsibility for management of the civilian high-level waste program and for characterization of the two potential waste sites for this program. The NWPA was subsequently amended in 1987 to establish Yucca Mountain, Nevada, as the single site to be characterized, with work on the second potential site to stop. The original NWPA also instituted a 1 mill/kwhre fee on all nuclear-generated electricity, to be paid into a designated Nuclear Waste Fund to be used for site characterization, construction and operation.

Another key provision of the NWPA was that it obligated the DOE to begin accepting SNF from utilities by January 31, 1998. However, the DOE recently served notice to the nation's nuclear utilities that it will be unable to accept used fuel at this time, and that a central, permanent storage facility will not be operational before 2010, at the earliest. This announcement has served as the impetus for two key actions. First, nuclear utilities, whose spent fuel pools are in many cases currently at or near capacity, have begun to build more dry cask storage to deal with the additional spent fuel that they will have to store on site as a result of DOE's inaction. Second, the Washington D. C. Court of Appeals ruled in 1996 that the DOE has a legal obligation to take SNF beginning on January 31, 1998 and that utilities can legally default on their 1 mill/kwhre payments to the Nuclear Waste Fund until the SNF is taken.

By not meeting its obligation, DOE has contributed to the current deadlock on the HLW issue, both directly and indirectly. Directly, the DOE has used more than half of the Nuclear Waste Fund (~\$6B of a total of \$11B) and has made little apparent progress to date. Indirectly, the DOE has created an adversarial relationship with the utilities through its inaction. This may make it difficult to collect more money for the Nuclear Waste Fund, especially since utilities are currently allowed to default on payments, and to continue progress, given the potential for exhausting the pre-paid financial resources. Since utilities are being forced to pay for the dry cask storage necessary to deal with the spent fuel that the DOE should have collected, most are putting the SNF in single-purpose cannisters, which are cheap, not licensed for transportation, and can only be used for storage. If the DOE would have successfully worked more closely with the utilities, either by meeting its obligation to collect the SNF or by providing economic incentives and support for on-site storage, utilities might have been more likely to use dual-purpose (storage and transportation) or even tri-purpose cannisters (storage, transportation, and disposal) to store their fuel. This would have prepared the SNF for shipping (and possibly disposal) at the reactor sites and would have avoided the time delays to re-package the waste and the additional money that the DOE may have to reimburse the utilities for their temporary storage solution.

Not only has the DOE created an adversarial relationship with the utilities, but it has also angered taxpayers, who may be forced to pay up to \$56B (in 1997 \$) in liabilities as a result of DOE failing to meet its obligation. While most taxpayers may be unaware of the large potential liabilities involved with this issue, their respective Congressional representatives are more than likely aware of the situation and acting in their interests.

These liabilities stem mainly from the cost of utilities being forced to store the spent fuel instead of having it taken away by DOE and the opportunity cost of supplying additional funds to the Nuclear Waste Fund beyond the January 31, 1998 deadline [N1].

Action has been taken recently within the US Congress to try to fix this problem. Bill S.104, the NWPA of 1997, was passed (65-34) in the Senate on April 15, 1997, and can be summarized in the following three, key points [N1]:

- Requires the DOE to design, build, and operate a central, interim storage facility at the Nevada Test Site to accept SNF from commercial nuclear power plants; creates a decision and licensing process that would lead to the storage of used fuel at a federal storage facility beginning no later than June 30, 2003, if all of the necessary approvals are obtained
- Establishes an integrated waste management system for the federal government for managing SNF
- Provides for a feasible funding plan in which the current funding mechanism is maintained (1 mill/kwhre fee on nuclear generated electricity). This fee will be tied to the congressional appropriation for the year in which the fee is collected, ensuring that these funds would be used for the Nuclear Waste Fund and not for deficit reduction, as in years past.

A similar bill was passed (307-120) in the House of Representatives. While there are differences between the House and the Senate bills (extraneous to the facets of the analysis in this chapter), their introduction and passage represent a commitment on the part of the legislature to resolve this issue. President Clinton has vowed to veto the bill that finally reaches him with these provisions because he seeks a permanent solution rather than a temporary stop-gap measure. The slim margin (with respect to the two-thirds majority to override the veto) by which the bills were passed (290 v. 307 in the House, 67 v. 65 in the Senate) shows that the fate of the law may rest on tenuous ground.

Given the huge economic and political problems associated with SNF generation in today's nuclear industry, a strategy that has the effect of exacerbating this already difficult issue, i.e. batch-loaded extended operating cycles, would certainly be opposed by all stakeholders: DOE, congress, rate payers, utilities, and environmental advocacy groups. However, implementing *multi-batch* extended operating cycles would reduce the volume of spent fuel that is generated annually, as compared to both batch loaded extended operating cycles and current practice. This comparison of spent fuel production is shown in Figures 2-6 and 2-7, repeated here as Figures 6-1 and 6-2.

Figure 6-1: Annual Generation of Spent Nuclear Fuel for Extended Operating Cycles in the Case Study BWR

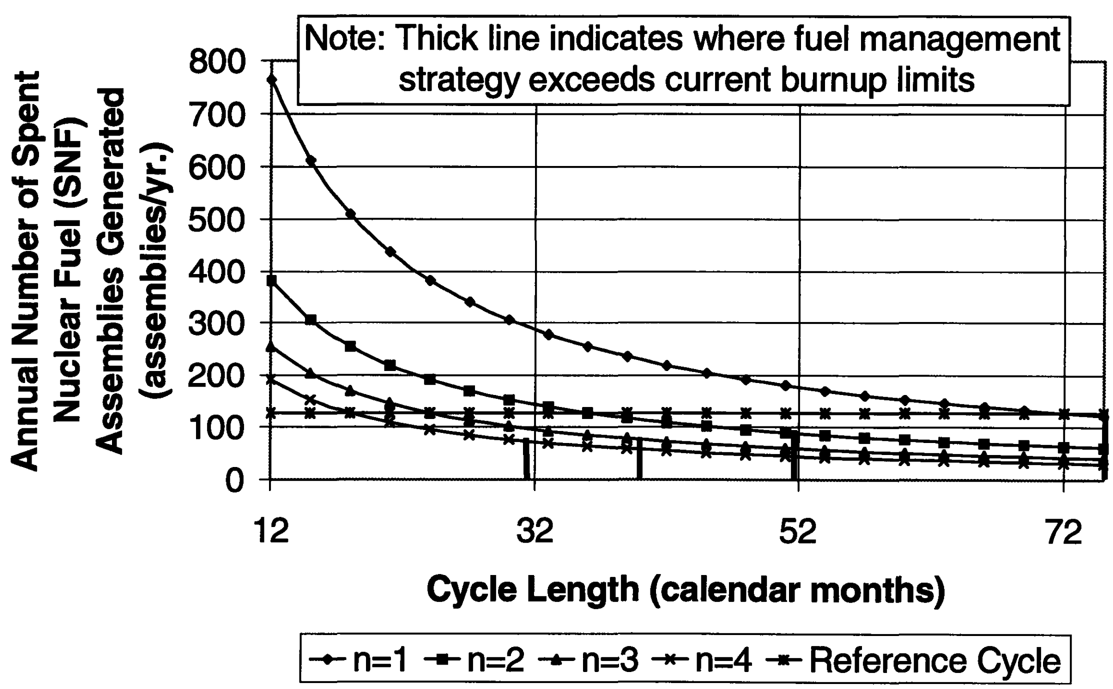
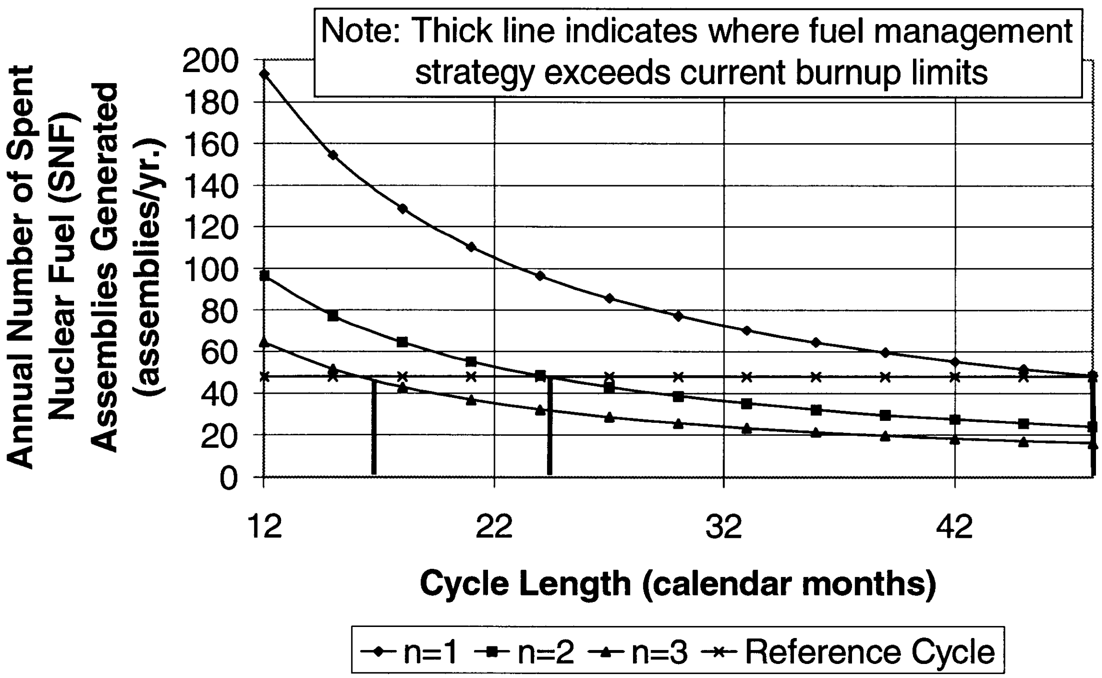


Figure 6-2: Annual Generation of Spent Nuclear Fuel for Extended Operating Cycles in the Case Study PWR



As n (batch index number, the inverse of batch fraction) increases for a fixed cycle length, the annual volume of spent fuel that is produced decreases. Combining these results with those found in Figures 4-7 and 4-8 shows that operating at longer cycles with multi-batch fuel management also yields economic benefits near those of the optimum strategy.

While running multi-batch cores at extended cycles might seem to be an ideal solution from a policy and economic standpoint, several technical issues may hinder implementation of such a strategy. First, as shown in Figures 6-1 and 6-2, multi-batch extended operating cycles exceed current NRC-mandated burnup limits. Second, such strategies will challenge neutronic and fuel design limits. Extended cycle multi-batch cores will require enrichments exceeding the current licensing limit of 5 $^{w}/_{o}$ U-235 and will operate with much more reactivity in-core. While similar problems have been addressed with batch-loaded extended cycles, these issues will need to be investigated for multi-batch extended operating cycles to identify and solve any unique challenges in these areas. With respect to fuel performance, potential impediments similar to those found for single-batch extended cycle management have been identified: waterside corrosion, cladding axial growth, rod internal pressure, and loss of fuel mechanical integrity [S2]. While the batch-loaded scheme poses unique problems in these areas due to the long in-core residence time without shuffling, a multi-batch strategy would mitigate these deleterious effects of extended cycles by shuffling the fuel. However, this would come at the expense of a longer total in-core residence time than with current practice and more importantly, higher fuel burnup.

Because of the technical issues associated with multi-batch (high burnup) extended operating cycles, an intensive research and development program directed at these and other issues would need to be undertaken before this (partial) solution to the SNF problem could be implemented. The DOE is planning to undertake such an initiative, the "High Efficiency Nuclear Fuel Program," which seeks to reduce the rate of SNF generation in US LWRs by increasing both the burnup limits and the average fuel in-core residence time. The research presented in this report as well as that done by other members of the extended cycle group would serve as a good starting point for this program, since the MIT project both generically and specifically addresses many of the technical and economic issues associated with implementing extended operating cycles.

R&D initiatives such as the DOE example cited above which seek to help the SNF issue are necessary if extended operating cycles are ever to come to fruition, especially if market conditions and technology change such that extended operating cycles become economically viable. Additionally, such proposed solutions will help mitigate the effects of a problem that has been the center of a contentious policy debate for the past two decades. Consequently, the DOEs "High Efficiency Nuclear Fuel Program" as well as other initiatives aimed at achieving the goal of cost-effective spent-fuel reduction should be supported by the federal government and utilities alike, who are both faced by this problem.

6.3 Development of advanced uranium separation technologies

Realization of technologies which decrease the cost of enriching uranium hold the most certain and feasible way to make extended cycles economically viable. This stems mainly from the fact that extended cycles stand to save more from lower enrichment costs than current practice since they use higher enrichments. This margin of savings can exceed the cost penalty existing between extended cycles and current practice of other economic factors, as discussed in Chapters 2 through 4.

Current uranium enrichment technologies include gaseous diffusion and gas centrifuge methods. Both methods use gaseous uranium hexafluoride (UF_6) as the feedstock and rely on the mass differences between U-235, the fissile isotope of uranium, and U-238, the more-abundant, non-fissile isotope of uranium, to achieve separation, i.e. enrichment. This is achieved by pumping the UF_6 through a semi-porous membrane (diffusion) or by spinning it at high speeds (centrifuge).

While current methods serve the enrichment needs of utilities and defense programs, research is currently being conducted by the United States Enrichment Corporation (USEC) into Atomic Vapor Laser Isotope Separation (AVLIS), which promises a cheaper, better solution to uranium enrichment. Using uranium metal feedstock instead of UF_6, AVLIS uses high-powered and precisely tuned lasers to selectively ionize U-235, leaving U-238 relatively unaffected. The U-235 ions are then collected on a charged collector plate and the product is an enriched uranium metal alloy (rather than enriched UF_6, which is the product with diffusion and centrifuge technology) [H1, U1].

AVLIS holds several advantages over current enrichment technologies. An AVLIS facility will use only about 5% of the power used by the gaseous diffusion plants and will require less capital investment than a new centrifuge plant. Since the uranium feedstock will not need to be converted both to and from UF_6, losses and costs associated with conversion will be eliminated. Less uranium will be needed to produce the same amount of enriched product because of the lower residual U-235 enrichment in the tails, decreasing the amount of nuclear waste generated. Finally, very high levels of enrichment can be achieved in a single step with AVLIS, providing great benefits for nuclear defense applications which typically use highly enriched uranium.

Given these benefits, AVLIS (and more advanced versions of this type of technology) may seem like a panacea for the uranium enrichment process (and more generally, isotopic separation). However, creating a low-cost enrichment technology provides opportunity for additional nations and organizations for access to special nuclear materials. Consequently, there are severely negative consequences associated with weapons proliferation. Creation of a low-cost, low-energy method for enriching uranium and separating isotopes provides nations and organizations the opportunity to build nuclear weapons, where economic and technical barriers had previously prevented their entry. With the spread of this cheap technology to additional countries, a heightened level of international vigilance and action will be necessary to ensure that the global community continues to move toward eliminating non-peaceful uses of nuclear technology.

Despite the proliferation concerns that advanced uranium enrichment technologies create, the US government has invested more than $1.5B in AVLIS since the early 1960s and currently invests $5M/yr. in Australia's SILEX (a uranium enrichment technology that is being developed that is similar to AVLIS) program. Recently, the US pledged its continued support for the development of AVLIS with the signing of the Energy and Water Appropriations bill (Public Law 105-62) which provides for an additional $60M to be spent on AVLIS development and keeps the AVLIS research infrastructure intact. Other nations, such as South Africa and Japan are also investigating ways in which advanced uranium separation technologies can be implemented. Additionally, research is going on at the university level to investigate ways of achieving isotopic separation using Molecular Laser Isotopic Separation (MLIS) methods, which promises SWU costs as low as $10/kg SWU (compared to the standard value of $110 used in this report) [U1, E3].

The redundancy of efforts for finding more energy and cost efficient methods for enriching uranium as well as the continued support of the federal government gives promise to the economic viability of extended operating cycles. Further, the upcoming completion date of the first US AVLIS plant in 2004 (projected by USEC) provides hope for revolutionizing the uranium enrichment market and consequently, improving the likelihood of success of extended operating cycles. Research and development in this area is a necessary element of this success and should be continued in the interest of keeping nuclear power plants economically viable through current practice as well as the use of the proposed new operating strategy. However, issues associated with transfer of advanced uranium enrichment technology and the proliferation implications need to be addressed before they roadblock the implementation of a vital cornerstone of extended cycle success and nuclear power longevity.

6.4 Effects of a deregulated energy market

Given the impending deregulation of the electric utility industry, how a nuclear power plant using extended operating cycles would operate in such an environment, given resolution of the previous two issues, is a crucial part of an economic and policy analysis. While the economic effects of market conditions predicted to exist in a de-regulated market were discussed explicitly in Chapter 4, the policy implications associated with these effects as well as other issues associated with a deregulated market are explored in this section.

As with several other industries over the past two decades, the electric utility industry currently faces a nationally mandated shift from a regulated, state and federally-controlled system to a de-regulated, competitive market. This restructuring applies only at present to the generation of electricity, as competition for transmission and distribution would pose prohibitively large logistical and economic barriers.

Beginning with the 1978 Public Utilities Regulatory Policy Act (PURPA) and codified in the Energy Policy Act of 1992, deregulation of the electric utility industry is supposed to (1) provide electricity consumers with cheaper electricity and (2) make entry into the electricity generation business easier. Since electricity will now be bought and sold in a competitive market, i.e. based on price, electricity generating units with higher costs will be forced to either cut costs or face elimination. Additionally, small and cheap generating units, i.e. co-generation units, will be able to profitably and easily enter the electricity market, meeting the growing demand for electricity and potentially undercutting more expensive producers. This ability lies mainly in the fact that electricity is a commodity-like good and that the only differentiating factor, reliability, may not be as important to some consumers (residential) as it is to others (industrial). It is predicted by several analysts that these smaller, cost-effective units as well as other generating facilities will be absorbed by larger power generating firms who have the capital to competitively operate a fleet of cost-competitive electricity generating facilities. Thus, deregulation is predicted to have the effect of decreasing the number of traditionally defined "utilities" in the United States [B2, C4].

Nuclear power plants (NPPs) generally produce electricity at a higher total cost (although a competitive operating cost (in 1995 values): 3.77 cents/kwhre for oil, 2.68 cents/kwhre for gas, 1.92 cents/kwhre for nuclear, and 1.88 cents/kwhre for coal), mainly because they are burdened with higher capital and regulatory costs than their counterparts [F1]. With de-regulation, these plants will be forced to compete with lower-cost power producers and are predicted to be driven out of business unless they can become cost-competitive. This is a problem for NPPs because they may be unable to recover their capital costs and these costs will become "stranded." Not only do nuclear utilities face the problem of stranded costs, but the entire electric utility industry faces stranded costs on the order of $200B, one -third of which can be attributed to unrecovered capital costs from nuclear power plants [F1].

At the heart of this issue for NPPs is how these sunk, capital costs will affect operating costs, i.e. competitiveness in a de-regulated market. The three extreme solutions to dealing with these costs present the boundaries to the competitive situation of nuclear power in a deregulated market: (1) utilities will be reimbursed fully for their stranded costs by a surcharge on all electricity, not affecting their already competitive operating costs, (2) utilities will be forced to absorb some or all of the stranded costs and will raise electricity prices to recover these costs, or (3) utilities will be forced to absorb some or all of the stranded costs and will do so through the devaluation of their equity, mitigating the effect of cost recovery on operating costs. While utilities are lobbying for the first solution since it represents their most favorable possible outcome, they will more than likely be exposed to at least part of one of the latter two. This will mean an increase in operating costs, an increase in the user cost of capital (due to the increased risk that shareholders were exposed to from the devaluation of equity) for future projects, or both and a subsequent disadvantage in a competitive energy generation market. Thus, deregulation presents large economic challenges for utilities owning nuclear power plants. Deregulation is also a concern for the Nuclear Regulatory Commission (NRC) which would be faced with the burden of a prematurely shut down plant.

Since competition in the electricity generation market will be based primarily on price and the stranded costs that the nuclear utilities face are sunk, NPPs will need to streamline their variable costs, i.e. operations, in order to lower the price of the electricity they produce. This focus on operations and maintenance (O&M) issues would be consistent with the shift from reactor design to O&M issues that has been occurring in the US nuclear power industry over the course of the past decade. This shift in emphasis is mainly due to the stagnation of nuclear power plant design and technology resulting from the lack of orders for nuclear power plants and lack of support for nuclear power since the Three Mile Island (TMI) incident. This shift can also be attributed to the fact that a large number of problems that the US nuclear power industry has faced since and including TMI have been due to human factors, management issues, and low capacity factors.

A regulatory implication that is currently and will continue to be faced as a result of streamlining and deregulation is the delicate balance between economics and safety. A new approach that proposes to maintain this balance is performance-based regulation, which dictates that the required surveillance intervals on nuclear power plant components be based on their history of performance instead of currently prescribed limits. While performance-based regulation would certainly decrease the costs of nuclear power plants operating with extended and current operating cycles, the Nuclear Regulatory Commission is being cautious about implementing this new approach to plant maintenance because of safety concerns. Should this method be found to provide adequate margins of safety, it could be implemented to provide NPPs with an added measure of competitive security in a deregulated market. While performance based regulation does not have unique implications for extended operating cycles, it would certainly provide benefits and would contribute to making this new operating strategy more economically viable.

Two issues that are of concern for extended operating cycles in a deregulated energy market are the cost of replacement energy and the carrying charge rate (discussed in Sections 4.4.1 and 4.4.2). Since replacement electricity will be bought and sold based on "spot" market prices which are predicted to be somewhat volatile and higher, replacement energy costs will mean higher costs for nuclear power plants, and utilities operating these plants will need to somehow insure against these potentially high prices. One option is to hedge against high prices by purchasing forward contracts on electricity prices. However, given the expected price volatility, a significant risk premium may be charged. As an alternative, utilities with nuclear power plants could also provide their own replacement energy with other, cheaper generating sources. While utilities would not have to pay for replacement electricity from the market with this scenario, there is an opportunity cost associated with this scenario equal to the difference between the market price and the cost of the cheaper generating unit.

Since the utilities that are hypothesized to exist in a competitive market will be large and diverse, the incremental loss of generation from NPP downtime as compared to the total capacity of a utility would probably be small. Thus, replacement energy costs for NPP downtime may not be as large of a concern in a deregulated market as larger utilities will be better prepared to absorb these costs and make them up elsewhere. However, utilities will still seek to decrease costs in this area in an effort to remain competitive. This differs from the currently regulated market, where the distribution system is responsible for providing electricity to consumers; in a deregulated market, electricity generators will be responsible for this replacement energy.

Since the costs of extended operating cycles are less sensitive to replacement energy costs than current operating strategies because of the extended cycle's inherent operational benefit, i.e. they require less replacement power, this new operating strategy poses a unique benefit for a de-regulated energy market where volatility of replacement energy costs is sure to exist.

Carrying charge rate is also a concern for extended operating cycles. Since there will be increased risk, i.e. uncertainty, about the electricity market in a competitive environment, the carrying charge rate on nuclear fuel will inevitably increase. As utilities become more like conventional businesses, debt (bond) financing will decrease relative to equity (stock) financing, which will also increase their cost of money. An increase in carrying charge rate will be more of a concern for utilities looking to build new nuclear plants, as the larger cost of money for these capitally-intensive ventures will have a significant effect on the economic viability of these projects.

Extended operating cycles have both an inherent disadvantage and advantage with respect to carrying charge rate. As cycle length increases, so does the effect of discount rate on cost, making the effect of this changing parameter more pronounced for extended operating cycles. However, as carrying charge rate increases, the optimum extended cycle length changes only slightly, providing for a scenario in which a nuclear power plant operating at this optimum strategy will be doing that best that it can, given changing market conditions. Thus, extended operating cycles could provide for security against a fluctuating discount rate in a deregulated market, as the optimum cycle length does not shift much with a change in this factor.

There are other economic factors that must be considered that make extended operating cycles uniquely attractive in a deregulated market. If operations are really improved, i.e. higher capacity factors, due to this innovative strategy, there are short-term economic benefits of requiring less replacement energy to be purchased, making nuclear power plants more cost-competitive. In the long term, better running plants eliminate the need for reserve capacity plants to be built to meet electricity demand, another cost savings.

6.5 Nuclear power as security against global warming

With recent concerns about global warming, unilateral actions have been taken in an effort to address this environmental concern. While there is considerable scientific debate about whether or not a problem actually exists, the growing concerns about global climate change have served as the impetus for nations to take active measures in reducing Greenhouse Gas (GHG) emissions and to look for ways of producing energy with fewer and cleaner emissions. Because they do not emit any GHGs, nuclear power plants appear to be an attractive solution for supplying energy needs. However, given that the nuclear power option has fallen into disfavor and has become economically unattractive (especially in comparison with combined cycle gas turbines) in most of the western nations which today create most of the GHGs, this option for addressing global warming is unlikely to be used to its fullest potential. This is especially a problem in the United States, in which utilities have not ordered a new nuclear power plant since before the Three Mile Island incident, and produces over a quarter of the world's GHGs.

With the resolution or mitigation of the SNF issue, the lowering of operating costs due to the implementation of advanced uranium enrichment technologies, and successful transition to a deregulated energy market, extended operating cycles will contribute to the viability of nuclear power that can be harnessed to help mitigate the effects of this global environmental concern. Continued safe and economic operation of current plants is a necessary condition to deployment of more in the future.

6.6 Summary and conclusions

While extended operating cycles have been shown to be technically feasible, the economic and policy barriers which exist to successful implementation must be considered and resolved if such a strategy is to become viable. The three key policy issues that must be dealt with successfully are increased generation of spent nuclear fuel (SNF), development of advanced uranium separation technologies, and the competitive market that nuclear power plants will face at the time that extended cycles would be implemented. The solution to effectively handling the issue of SNF while maximizing the economic benefit from extended operating cycles is to invest in research and development (R&D) on increasing allowable burnup limits which permit multi-batch extended operating cycles. Investment in R&D is also a crucial part of implementing advanced uranium separation technologies, which hold the promise of improving the economic position of nuclear power, incrementally under current practice and significantly through the use of extended operating cycles. Additionally, extended operating cycles may provide insurance against uncertainty in the deregulated energy generation market in which they will operate. Should these factors be resolved and extended operating cycles become economically competitive, nuclear power could become revitalized and provide a sustainable approach to helping solve the hypothesized global warming crisis, while assuring energy security.

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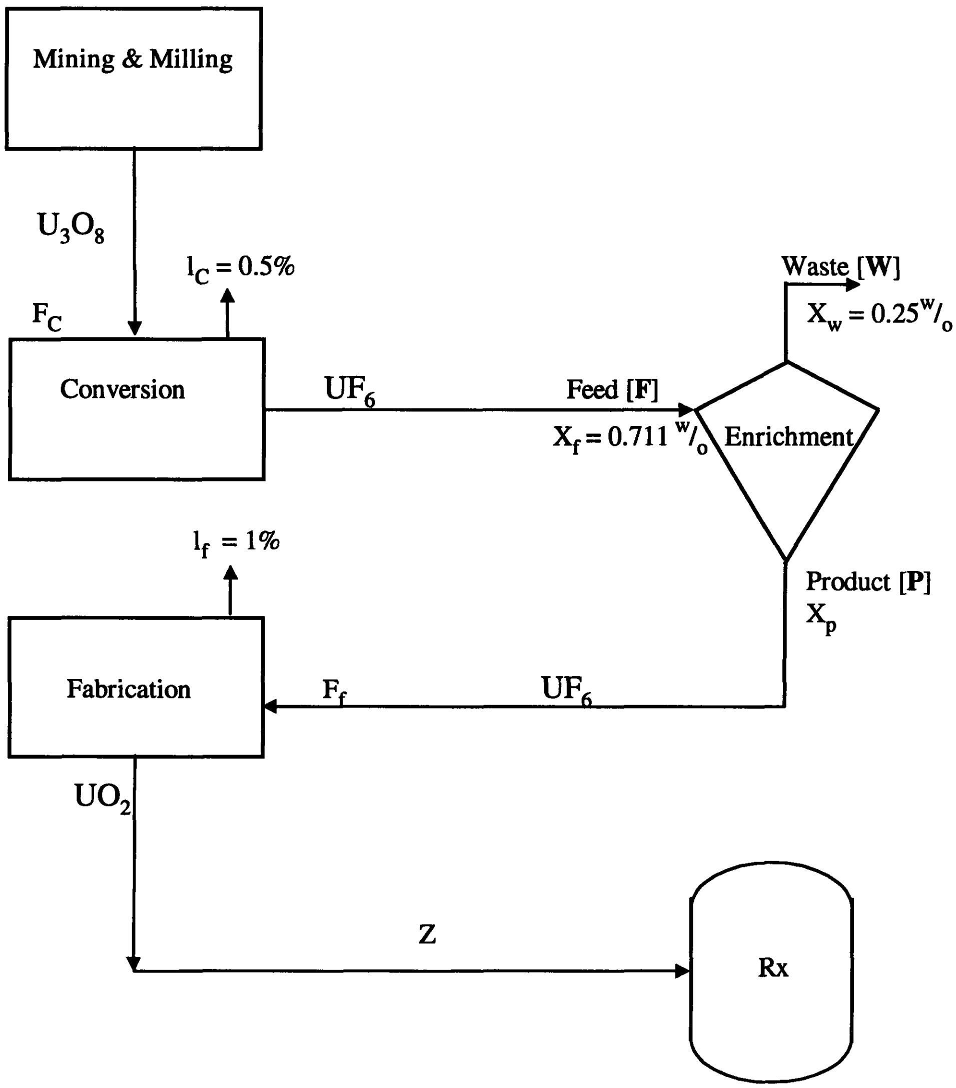
Appendix A: Front End Fuel Cycle Flowchart and Calculations

The flowchart of the front end of a typical fuel cycle is drawn below, from the mining of the uranium ore to the delivery of fuel to the plant:



In order to calculate fuel costs, the following formulae are used to determine the mass flow rates of each process step, M_i; that is, the kg per process step needed to produce 1 kg of Heavy Metal Uranium (HMU) for use in a reactor.

Assuming that the reactor requires Z kg of HMU, then the number of kg of U in UO_2 that must be fabricated is also Z, making the mass flow rate from fabrication in all cases 1.

$$M_f = \frac{Z}{Z} = 1 \qquad \{A\text{-}1\}$$

To find the amount of U as UO_2 that must be fed into the fabrication process:

$$F_f = \frac{Z}{1 - l_f} \qquad \{A\text{-}2\}$$

where: F_f = mass of feed into fabrication process, kg U
l_f = fraction lost in fabrication process, 0.01 in this case

Next, we are interested in the amount of uranium that must be fed into the enrichment process. This can be shown by the following relationship [B1]:

$$F = \left(\frac{x_p - x_w}{x_f - x_w}\right)P \qquad \{A\text{-}3\}$$

where: F = mass of feed into enrichment process, kg U
P = mass of product from enrichment process, kg
= F_f in this case
x_p = enrichment of product, $^{w}/_{o}$ U-235
x_f = enrichment of feed, 0.711 $^{w}/_{o}$ U-235 in this case
x_w = enrichment of tails, 0.25 $^{w}/_{o}$ U-235 in this case

Since enrichment is priced by the number of Separative Work Units (SWU) that must be expended to enrich uranium, the kg SWU for enrichment, or SWU to Product ratio can be found by [B1]:

$$M_e = \frac{SWU}{P} = \left[(V_p - V_f) - (x_p - x_f)\left(\frac{V_f - V_w}{x_f - x_w}\right)\right] \qquad \{A\text{-}4\}$$

where: SWU/P = SWU to product ratio
V_p = value function of the product
V_f = value function of the feed
V_w = value function of the waste
where: $V_y = (1 - 2x_y)\ln\left(\frac{1 - x_y}{x_y}\right)$ {A-5}
V_y = value function for material of enrichment x_y and y represents the product (p), feed (f), or waste (w)

Having found the amount of feed necessary for the enrichment stage, we can find the mass flow rate for the conversion process to be:

$$M_c = \frac{F}{Z} \qquad \{A\text{-}6\}$$

Finally, we can find the amount of U as Uranium ore that needs to be mined by taking into account the losses that are incurred as a result of conversion:

$$F_c = \frac{F}{1 - l_c} \qquad \{A\text{-}7\}$$

where: F_C = mass of feed into conversion process, kg U
l_C = fraction lost in conversion process, 0.005 in this case

Thus the mass flow rate for the mining stage can now be determined as:

$$M_m = \frac{F_c}{Z} \qquad \{A\text{-}8\}$$

It is these four derived mass flow rates upon which the fuel cost model explained in this report is based.

Appendix B: Methodology for Economic Analysis

B.1 Introduction

The economic analysis in this report is straightforward application of conventional engineering economics principles, as presented in a number of widely used textbooks, i.e. Ref [S-1]. In this discussion, four aspects will be documented: approximations made to facilitate the time-value-of-money calculations, handling of continuous cashflows, levelizing up-front costs, and conceptual factors related to the selection of an appropriate discount rate.

B.2 Algebraic Approximation of the Time Value of Money

The starting point is the expression for the future value (F) of a present sum (P) using continuous compounding:

$$F = Pe^{it} = P[1 + it + \ldots] \qquad \{B\text{-}1\}$$

where: i = interest rate

where the use of continuous compounding is not a limitation because of the transformation:

$$i = \ln[1 + \theta\zeta]^{1/\theta} \qquad \{B\text{-}2\}$$

where ζ is the interest rate per compounding period of duration θ.

In the fuel cycle analyses in Chapters 2 and 4, the reference time-zero point is defined to be the mid-point of the cycle of interest, with only the first order (i.e. linearized) term of the expansion in Eq. {C-1} retained, yielding:

$$F = P[1 + it] \qquad \{B\text{-}3\}$$

The error, ε, involved in present worth due to linearization is easily shown to be:

$$\varepsilon = \frac{\Delta P}{P} = \frac{(it)^2}{6} \qquad \{B\text{-}4\}$$

Then, for example, if i = 0.1/yr. and t = 3 yr., ε = 1.5%, which is tolerable for the purposes of this paper.

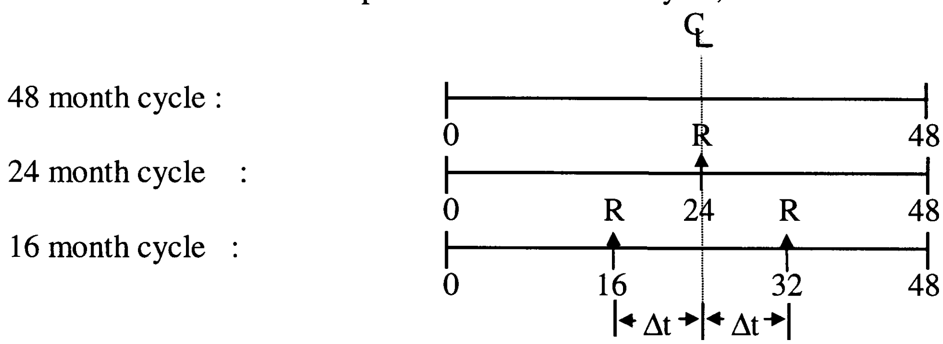
B.3 Handling of Continuous Cashflows

Also implicit in this analysis is replacement of a continuous cashflow, i.e. revenue from the sale of electricity, by a lump sum at the midpoint of irradiation, leading to an error, ε, of:

$$\varepsilon = \frac{(it)^2}{24} \qquad \{B\text{-}5\}$$

such that for i = 0.1/yr., t = 4 yr., ε = 0.7%, which is also quite negligible.

Finally, when estimating credit for avoided refuelings (R) and associated replacement energy charges, cycles of length other than 48 months are symmetrically situated relative to the mid-point of the 48 month cycle, i.e.:



Furthermore, it is assumed that upstream and downstream carrying charges cancel (exactly for linearized interest) such that only the direct costs need to be considered. In this case, the error, ε, is:

$$\varepsilon = \frac{(i\Delta t)^2}{2} \qquad \{B\text{-}6\}$$

Hence, ε is again trivial, at 0.5% for i = 0.1/yr. and Δt = 1 yr.

B.4 Levelizing up-front costs

To levelize an up-front cost (C_o) over a future span of time *t*, multiply the initial cost by the capital recovery factor for continuous compounding of a continuous cashflow, ϕ:

$$\Phi = \left[\frac{i}{1-e^{-it}}\right] \qquad \{B\text{-}7\}$$

Note that ϕ has the asymptotic value ϕ = i for sufficiently long t. However, this approximation was considered a bit too crude, and thus the full expression stated in Eq. {B-7} was employed in the estimates cited in Chapters 2 through 4. For the remaining plant life assumed in this paper, t = 20 yr., and for an assumed i = 0.1/yr., ϕ = 0.116, some 16% larger than i.

B.5 Conceptual considerations

Both exact and approximate procedures for linear depreciation of a capital asset, when the rate of return is a composite of equity and debt financing subject to taxation, have been developed and applied. Reference [S-1] discusses this topic in some detail; and Correa has published both summary and detailed analyses of versions which are particularly useful here [C-1, C-2]. We need only note here the following protocol for a useful approximate method:

(1) The appropriate discount rate is:

$$X = f_s r_s + (1-f_s) r_b \qquad \{B\text{-}8\}$$

where: f_s = fraction of equity funding
r_s = allowed or expected rate of return on equity
$(1-f_s) = f_b$ = fraction of debt (bond) financing
r_b = designated rate of return on bonds

Note that the cost of the debt (bond) financing is tax deductible.
(2) All cash flows are to be discounted at the rate X before or after irradiation
(3) During irradiation, while the asset (in this case, the fuel) is earning revenue, the carrying charge fraction to be applied is:

$$\Phi = \frac{X}{1-\tau} \qquad \{B\text{-}9\}$$

where: τ = tax fraction

In the present analysis no distinction is made between ϕ and X. This can be viewed in two ways:

(a) taxes are ignored ($\tau = 0$), as in the IAEA studies of nuclear fuel cycle costs, cited as the source of our reference case cost parameters, or

(b) the discount rate is over-estimated in the pre- and post-irradiation periods, i.e. ϕ is used throughout in place of X.

In view of the resulting ambiguity, parametric studies of the effect of changing the value of ϕ are appropriate.

A more subtle consideration is the effect of cost escalation, which is often taken equal to the rate of monetary inflation, but may be larger or smaller due to growing resource scarcity, technical innovation, and economy-of-scale or learning curve effects. In principle, inflation is incorporated as one component in the "interest" rate (return/discount/carrying charge rates), unless one subtracts it out, as economists often do to work in "constant dollars" of some benchmark year.

So long as one confines comparisons to the period of a 48 month intra-refueling cycle (particularly as we have done in ± 24 month time spans about its mid-point) escalation is not a significant factor. The issue arises when one combines fuel cycle costs with other costs levelized over a longer period of time (such as the 20 years assumed for remaining useful reactor life in this report).

If costs are escalated at a rate *y*, and their present worth over the time period, T, levelized, one can show that the ratio of levelized (C_l) to time-zero cost (C_o) is given by:

$$\left(\frac{C_l}{C_o}\right) = \left(\frac{x}{x-y}\right)\frac{\left[1-e^{-(x-y)T}\right]}{\left[1-e^{-xT}\right]} \qquad \{B\text{-}10\}$$

which linearizes to:

$$\left(\frac{C_l}{C_o}\right) \approx 1 + y\frac{T}{2} \qquad \{B\text{-}11\}$$

For x = 0.1/yr. , y = 0.05/yr., T = 20 yr., Eq. {B-10} gives the ratio 1.462, while Eq. {B-11} yields 1.5 - a good approximation in view of the uncertainty involved in the prediction of y.

Thus, strictly speaking, each component of our fuel cycle costs should be multiplied by the factor [1 + y(T/2)] if we are to later add fuel cycle costs to up-front costs levelized over T. In other words, all costs should be consistently compared over the same time horizon.

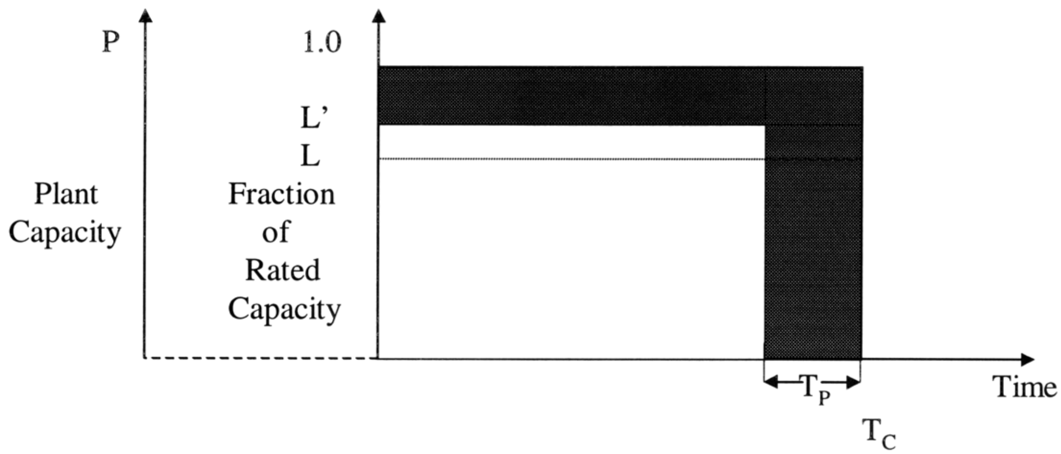
Such corrections were **not** applied in the present work on the basis that history shows that the net y, or net cost escalation rate, for nuclear fuel costs is apparently much less than pure monetary inflation, and perhaps zero or even slightly negative due to technical innovation and the existence of surplus market capacity (which induces suppliers to accept smaller profits). To some extent an equivalent positive y is inherent in our use of IAEA costs, which are projected future values, and higher than the current spot market values.

Appendix C: Derivation of Formulae

C.1 Derivation of Equation {1-1}

In Figure C-1, the energy that can be used during a typical operating cycle is shown in the white box, with the unusable capacity indicated by the shaded region.

Figure C-1: Energy Schematic For a Typical Operating Cycle



An energy balance can be derived to relate the capacity factor, L, the availability, L', the cycle length, T_C, and the planned, i.e. refueling (given the constraints of this report), outage length, T_P.

$$LT_C = L'(T_C - T_P) \qquad \{C\text{-}1\}$$

Rearranging this energy balance for capacity factor, L:

$$L = L'\left(\frac{T_C - T_P}{T_C}\right)$$

Finally, we get Eq. {1-1}:

$$L = L'\left(1 - \frac{T_P}{T_C}\right) = L'\left(1 - \frac{T_R}{T_C}\right) \qquad \{C\text{-}2\}$$

where: L = capacity factor
L' = availability
T_P = planned outage length, months
= T_R = refueling outage length, months (given the constraints of this report)
T_C = cycle length, calendar months

C.2 Derivation of Equation {3-4}

Looking at Figure C-1 we can find the unusable energy by multiplying the fraction of the total energy that will need to be replaced, F_e, by the total block of energy that could be used.

First, we find F_e by subtracting the capacity factor, i.e. useful energy found from Eq.{1-1} or {C-1}, from the total block of energy that could be used, 1:

$$F_e = \left\{1 - L'\left(1 - \frac{T_P}{T_C}\right)\right\} \qquad \{C\text{-}3\}$$

where: F_e = fraction of energy that needs to be replaced
L' = availability
T_P = planned outage length, months
= T_R = refueling outage length, months (given the constraints of this report)
T_C = cycle length, calendar months

To find the amount of energy associated with this fraction, or amount of replacement energy, E_R, we must multiply it by the total amount of energy, E_T, that could be used, or more simply, the size of the big box, $P*T_C$.

$$E_R = F_e * E_T * \left(\frac{365.25d}{12months}\right)\left(\frac{24h}{1d}\right) \qquad \{C\text{-}4\}$$

where:

$$E_T = P * T_C \qquad \{C\text{-}5\}$$

E_R = replacement energy, kwhre
P = full rated power of plant, kwe
T_C = cycle length, calendar months

Substituting in all values, Eq. {C-4} can be put in the form of Eq. {3-4}:

$$E_R = P * T_C * \left\{1 - L'\left(1 - \frac{T_R}{T_C}\right)\right\} * 730.5 \qquad \{C\text{-}6\}$$

C.3 Other Plant Performance and Economic Metrics

While capacity factor is being used as the metric for plant performance and economic comparison throughout this report, other ways of measuring these parameters are in use by organizations within the nuclear industry. As discussed in Chapter 1, the Institute of Nuclear Power Operations (INPO) uses capability factor as its plant performance criterion. Capability factor is defined as the percentage of maximum energy generation that a plant is capable of supplying to the electrical grid, limited only by factors within the control of plant management; a high unit capability factor indicates effective plant programs and practices to minimize unplanned energy losses and to optimize planned outages [I1]. Since this definition measures plant performance relative only to those factors within the control of plant manangement, i.e. planned and refueling outages, it can be expressed mathematically as:

$$CF = \frac{EFPL}{EFPL + T_P} \qquad \{C\text{-}7\}$$

where: CF = Capability Factor
EFPL = Effective Full Power Life of Core, months
T_P = length of planned outages, months
= T_R = length of refueling outage, months (given the constraints in this report)

Putting the equation for capacity factor, L,{C-2} in the terms used in the equation for Capability Factor {C-7} for the purposes of comparison yields:

$$L = \left(1 - \left(\frac{T_F}{T_F + EFPL}\right)\right) * \left(\frac{T_F + EFPL}{T_F + T_P + EFPL}\right) = \frac{EFPL}{T_F + T_P + EFPL} = \frac{EFPL}{T_C} \qquad \{C\text{-}8\}$$

$$\textit{where:}$$

$$L' = \left(1 - \left(\frac{T_F}{T_F + EFPL}\right)\right)$$

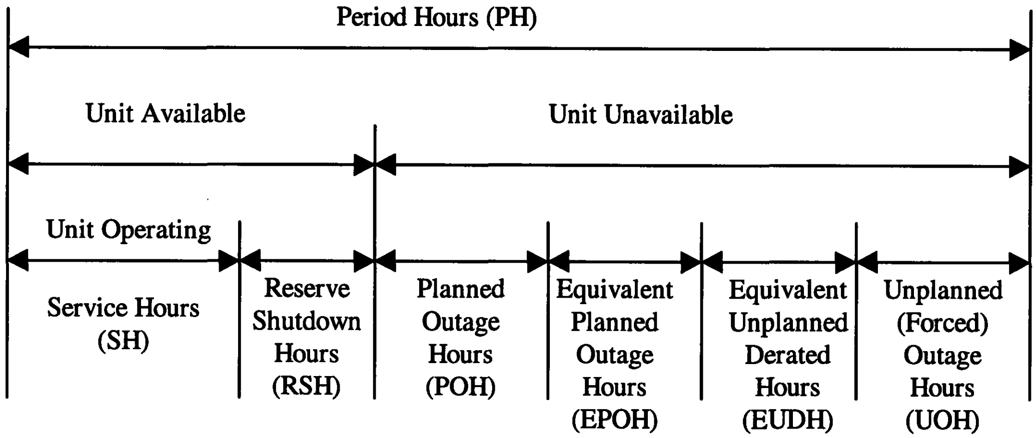
$$T_C = T_F + T_P + EFPL$$

where:
T_P = planned outage length
= T_R = refueling outage length (given the constraints of this report)
T_F = cumulative length of forced outage (per cycle)
T_C = cycle length
EFPL = Effective Full Power Life of Core
and all are measured in the same units of time

The key difference between capability factor and capacity factor is that capability factor does not account for the effects of forced outage when assessing plant performance. While this metric may be useful for an organization whose aims include improving planned outage, i.e. refueling and maintenance, management while maintaining an acceptable margin of safety, capability factor ignores the lost generation due to forced outage time and consequently is not a good tool for evaluating the electricity, hence revenue, generated by a nuclear power plant.

Another set of plant performance criteria that should be considered are those used by the Electric Power Research Institute (EPRI). Figure C-2 shows a schematic of the operating cycle and its components that EPRI uses in assessing plant performance, which comes from the EPRI Technical Assessment Guide (TAG).

Figure C-2: Operating Cycle and Components used by EPRI to Assess Plant Performance



EPRI's use of an operating cycle with all of the annotated component parts was developed for measuring the effects of a load following power supply (RSH) and more generally, an electric utility with many sources of generation. In this report, analysis has been confined strictly to a base-loaded nuclear generating unit as a means of accurately comparing different scenarios. Applying these restrictions to the EPRI model yields the following equivalences:

$$EFPL = SH + RSH \qquad \{C\text{-}9\}$$

$$T_F = EUDH + UOH \qquad \{C\text{-}10\}$$

$$T_R = POH + EPOH \qquad \{C\text{-}11\}$$

$$T_C = PH \qquad \{C\text{-}12\}$$

Applying Equations {C-9} through {C-12} to Equation {C-8} and Equation {C-7} yields:

$$L = \frac{EFPL}{T_C} = \frac{SH + RSH}{PH} = \frac{PH - (EUDH + UOH + POH + EPOH)}{PH} = \text{EA} \qquad \{C\text{-}13\}$$

$$CF = \frac{EFPL}{EFPL + T_R} = \frac{SH + RSH}{(SH + RSH) + POH + EPOH} \qquad \{C\text{-}14\}$$

Equation {C-13}, capacity factor (L), is equivalent to the EPRI metric Equivalent Availability (EA). This differs from EPRI's standard of Operating Reliability, defined as the percentage of energy demand period (period hours minus reserve hours minus planned outage hours) that the unit is capable of full energy production at its rated power output:

$$OR = \frac{PH - RSH - POH - EPOH}{PH} \qquad \{C\text{-}15\}$$

where: RSH = 0 under the constraints imposed by this report

From this definition, it is clear that OR does not account for the lost generation due to unplanned, i.e. forced, outages, similar to capability factor. Thus, of the three metrics considered, capacity factor (or EA) is the best tool for comparing different economic scenarios, given the purpose and constraints of this report.

Appendix D: Definition of Base Cases and Economic Parameters

	BWR Reference Cycle	BWR Extended Cycle	PWR Reference Cycle	PWR Extended Cycle
Case Study Plants				
Plant Type	General Electric BWR 4/5		Westinghouse 4-loop	
Thermal output (MW_{th})	3380		3411	
Electrical output (MW_e)	1100		1150	
Type of fuel used	Siemens Atrium-10		Westinghouse 17x17	
Number of assemblies	764		193	
Rated Specific Power (kW/kg U)	24.5		38.7	
Core Inventory (MTHMU)	138.7	135.504	88.18	85.3975
Number of type in US fleet/ Total number B/PWRs	14/37		27/72	
Operating Parameters				
Cycle Length (months)	24	47.8	18	41.4
Batch Number Index (n)	3	1	2.68	1
Refueling Outage Length (days)	49	42	49	42
Forced Outage Rate (%)	6	3	6	3
Resulting Capacity Factor (%)	87.7	94.2	85.6	93.8
Fuel Cycle Economic Parameters [O1]				
Uranium purchase	$50/kg U			
Conversion	$8/kg U			
Enrichment	$110/kg SWU			
Fabrication	$275/kg U			
Waste disposal fee	1 mill/kwhre (U.S.)			
Replacement power	25 mills/kwhre			
Carrying charge rate	10%/yr.			
Fuel Cycle Data [O1]				
Tails assay for enrichment	0.25%			
Lead time for:				
Uranium Purchase	24 months			
Conversion	18 months			
Enrichment	12 months			
Fabrication	6 months			
Loss factor for:				
Conversion	0.5%			
Fabrication	1.0%			

SECTION II: Fuel Performance Analysis of Extended Operating Cycles in Existing LWRs

CHAPTER 1: STEADY STATE FUEL PERFORMANCE CRITERIA

1.1 Introduction

Given a soon to be deregulated electricity market, nuclear power plants (NPPs) are looking for ways to become more economically competitive. One such proposed way is to operate NPPs at extended cycle lengths, avoiding costly refueling outages, decreasing the down time through decreased frequency of infant mortality effects, and spreading costs over a longer horizon. Analysis of these economic and availability effects has already been made and results have shown that while increased availability is an inherent quality of extended cycles, improved economic performance is not, given current market conditions [H1, B1]. In conjunction with these studies, other research has been conducted to design both BWR and PWR long cycle cores in an effort to assess technical feasibility [M2]. These core designs were performed at or near the limit of technical feasibility with the idea that any extended cycle length intermediate to this ultra-long limit and current practice would be well within the feasible design envelope.

While an extensive neutronic analysis and design were performed for both the case study BWR and PWR, issues associated with the performance of the fuel were only addressed briefly. This area of investigation is important because there are many technical issues that exist at the micro-core level that could present potential barriers to implementation of an extended operating cycle strategy. This report will focus on defining these issues, assessing their impact, and proposing solutions where applicable. These issues will be addressed in the context of steady-state operations for two reasons: (1) steady-state operations provide the broadest and most comprehensive arena for addressing fuel performance issues and (2) steady-state is the first step in determining the technical feasibility of nuclear power operations; if a criterion is violated in steady state, it will certainly be violated during more severe transient conditions. The parameters and characteristics used to assess the technical feasibility in this report are consistent with those used in the core design report and are outlined in Table 1-1.

Table 1-1: Parameters and Characteristics of the Case Study LWRs

	Case Study BWR		Case Study PWR	
Type	General Electric BWR 4/5		Westinghouse 4-loop	
Thermal output (MW_{th})	3380		3411	
Electrical output (MW_e)	1100		1150	
Type of fuel used	Siemens Atrium-10		Westinghouse 17x17	
Number of assemblies	764		193	
Specific power (kW/kg)	24.5		38.7	
Number of type in US fleet/ Total number B/PWRs	14/37		27/72	
	Ext. Cycle	Ref. Cycle	Ext. Cycle	Ref. Cycle
Batch index number	1	3	1	2.68
Cycle length (calendar mo.)	47.8	24	41.4	18
EFPM (months)	45.0	21.1	38.8	15.5
Capacity factor (%)	94.2	88	93.8	86

As with all aspects of designing a nuclear power plant, there is prescriptive literature on standards for design and licensing of nuclear fuel. Sections 4.2 and 4.4 of the U. S. Nuclear Regulatory Commission's Standard Review Plan (USNRCSRP) provide guidance on the criteria that should be addressed when designing or operating nuclear fuel. Section 4.2 addresses fuel system design and will provide most of the basis of this report; section 4.4. is concerned with thermal and hydraulic design and will be used specifically when addressing cladding overheating concerns, i.e. Critical Heat Flux (CHF).

There are four main objectives of Section 4.2 [N1]:

- The fuel system is not damaged as a result of normal operation and Anticipated Operational Occurrences (AOO).
- Fuel system damage is never so severe as to prevent control rod insertion when it is required.
- The number of fuel rod failures is not underestimated for postulated accidents.
- Coolability is always maintained.

Since this report is focusing on steady state issues, only the first two objectives are of importance here. "Fuel system damage," the basic criterion that is being measured in this analysis, can be defined as when fuel rods "fail," fuel system dimensions exceed operational tolerances, and functional capabilities are reduced below those assumed in the safety analysis. "Fuel rod failure" can be defined as the fuel rod leaking, breaching the first fission product barrier (the cladding).

Table 1-2: Steady State Fuel Performance Criteria by Category[1]

Fuel System Damage	Fuel Rod Failure
(1) Stress, strain and loading limits for fuel system structural members should be provided	(7) Primary hydriding is to be limited
(2) The cumulative number of strain fatigue cycles should be significantly less than the design fatigue lifetime	(8) Cladding collapse should be avoided
(3) Fretting should be limited	
(4) Oxidation, hydriding, and build-up of corrosion products (CRUD) should be limited	(9) Overheating of cladding should be prevented
(5) Dimensional changes such as rod bowing or irradiation growth of fuel rods should be limited.	(10) Centerline melting of the fuel pellet is not permitted
(6) Fuel and burnable poison rod internal gas pressures should remain below nominal system pressure unless otherwise justified	

[1] See Ref. [N1]

The acceptance criteria for steady state fuel performance are found in two different categories of the USNRC SRP: fuel system damage and fuel rod failure, listed in Table 1-2. All other criteria deal specifically with AOO or transient conditions [N1].

1.2 Consequences of failed fuel for extended operating cycles

The reason that fuel performance is such a concern with extended operating cycles is because of the significant consequences of a failed fuel rod. Most obviously, if a fuel rod fails, the first barrier to fission product release has been breached. This is a concern given the nuclear power industry's "defense-in-depth" approach to safety, as one of the barriers to radioactive release would no longer exist.

This breach also has consequences for worker safety in that failed fuel results in a release of radioactive fission products into the primary coolant. This release increases coolant activity levels, leading to increased radiation fields around components that plant personnel work on. This means that more workers would be needed to perform work in these higher radiation field areas in order to stay within individual dose limits, translating into additional costs and decreased productivity for nuclear power plants. This issue is especially pertinent as it has become a major goal of the US nuclear power industry, shown by the Institute for Nuclear Power Operations' (INPO's) use of the coolant activity metric Fuel Reliability Indicator (FRI) as a plant performance indicator.

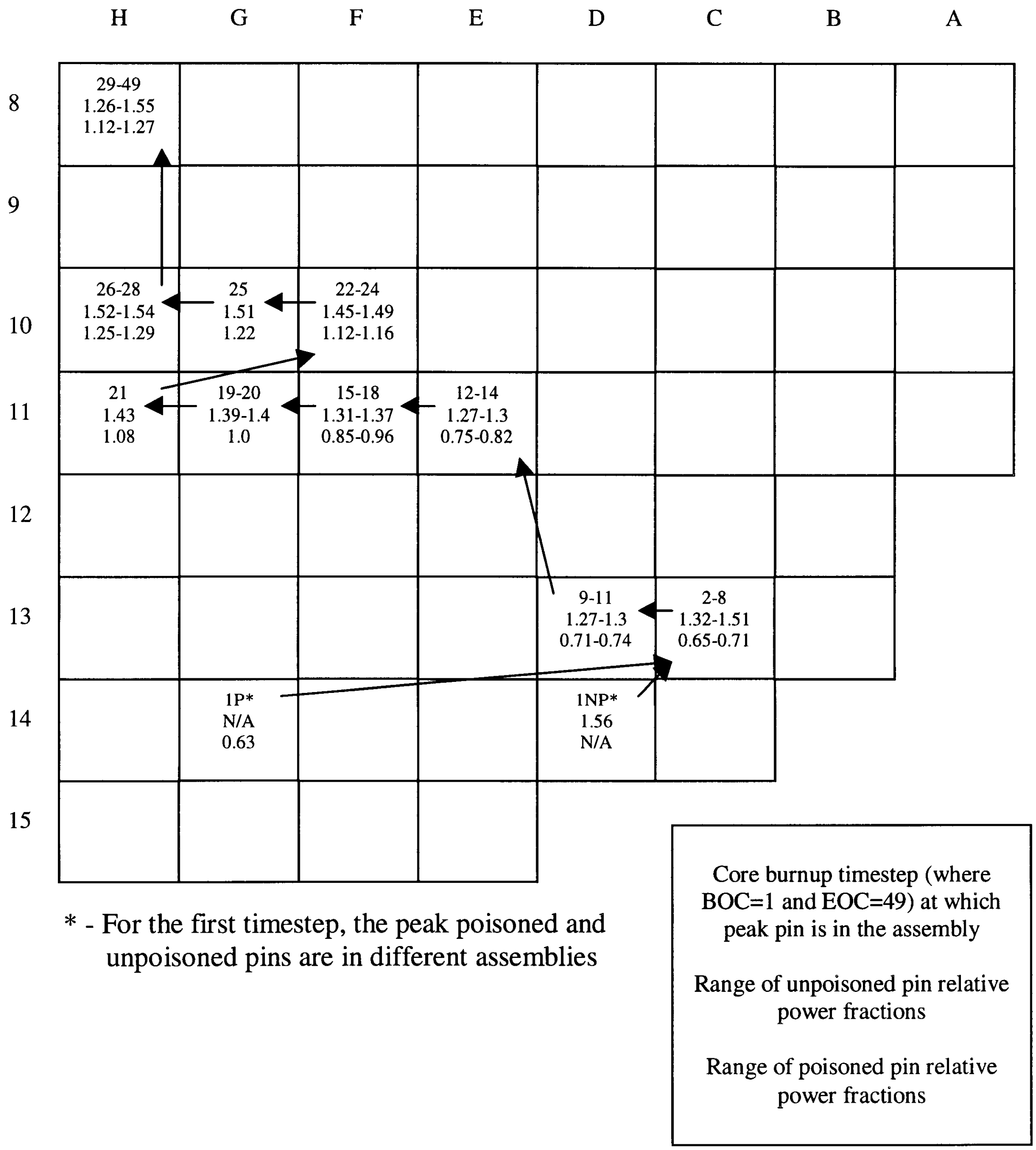
With respect to radioactive waste and plant operations, failed fuel also has negative consequences. Increased coolant activity will increase the amount of low level waste (LLW) created, again incurring more costs for the plant. Once a fuel rod has failed, the entire assembly will need to be removed from the reactor core. This will either halt operations or be performed during an outage, sometimes before the assembly has reached the end of its useful life. This translates into both costs because of the reactivity that is being thrown away and lost revenue from downtime (if operations must be interrupted to locate and remove the failed fuel or the outage time is extended as a result). This also increases the amount of high level waste (HLW) that is generated.

Additionally, once a fuel rod has been identified as failing, control rods around the failed fuel are often inserted in an effort to decrease the amount of fission products being created in the region of the failure. With as few as 1-5 control rods inserted, the level of power output can be reduced, equating to lost generating revenue. Additionally, inserting these control rods creates a large flux gradient, which can have an adverse effect on the fuel performance of fuel elsewhere in the core. The fuel around the failed rod will also be under-burned as a result of control rod insertion, and consequently this fuel would not reach the end of its useful life [P1]. Given the many safety, economic, and operational consequences of failed fuel, it is obvious why fuel performance is an important issue worthy of close research when implementing a new operating strategy.

1.3 Creation of an envelope pin

Since some extended cycle fuel pins will burn in hotter regions of the core for long periods of time, it is important to find a way to quantify the deleterious effect this would have. Following a given fuel pin throughout core life is one way of doing this; however, this method falls short given that both the location and power of the peak pin in a reactor core shifts often. The peak pin location not only resides in different assemblies over core life, but also changes location within an assembly. The latter effect is too hard to show, while the former effect is illustrated in Figure 1-1. This effect of shifting peak power is more pronounced in the extended cycle core for the case study BWR where the assembly location of the peak pin changes virtually every timestep. Consequently, it is hard to quantify which single pin will burn at the highest power for the longest period of time.

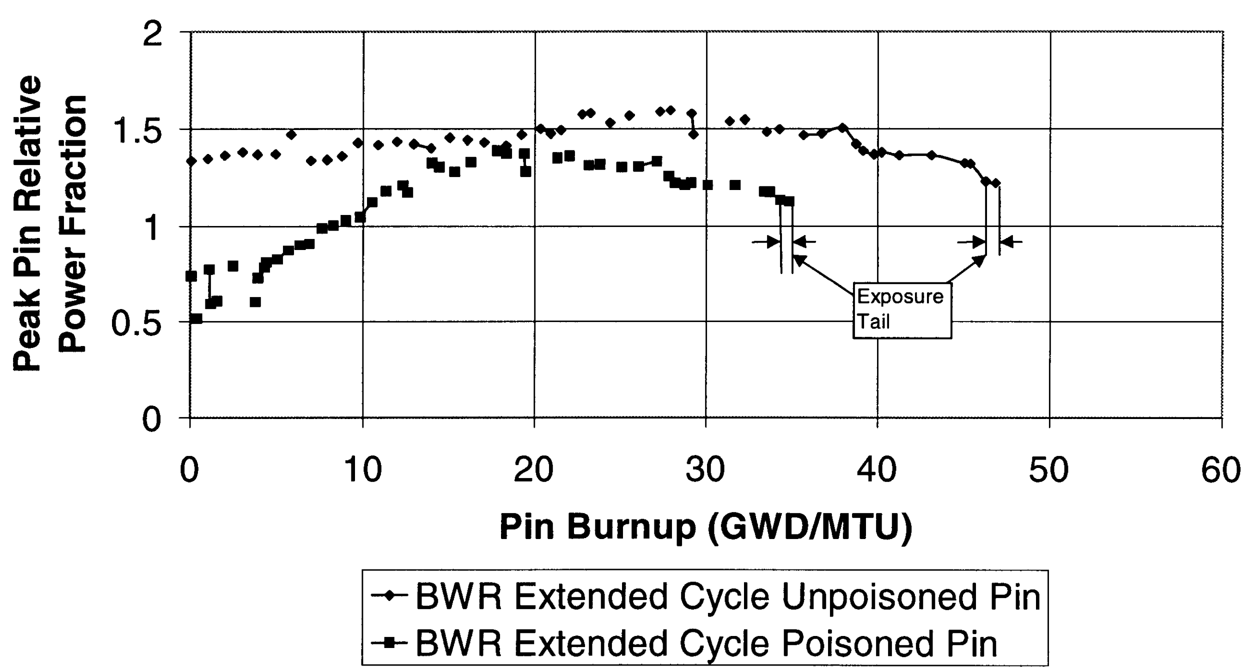
Figure 1-1: Location and Power of the Peak Pin in the Case Study PWR Extended Cycle Core



* - For the first timestep, the peak poisoned and unpoisoned pins are in different assemblies

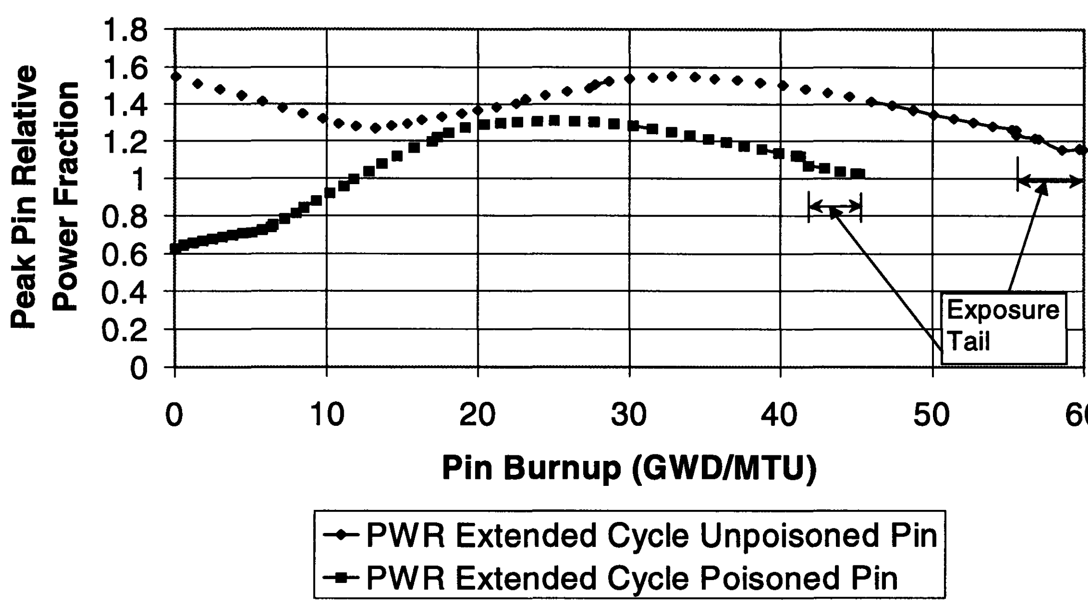
Therefore, an alternative method was sought. Consistent with industry practice, the hottest pin at each cycle burnup step was tracked and its power history at each of the corresponding pin burnup steps (i.e. axial flux shape, relative power fraction (also known as $F_{\Delta h}$ for PWRs)) was used to create a pseudo-pin that would represent a worst-case scenario [S1]. In order to insure that the envelope pin represented the full range of pin burnups seen in these core designs, the highest power pins at burnups beyond the "peak pin" burnup at end of cycle, i.e. the exposure tail, were included. This method was used to create two separate envelope pins, one representing unpoisoned pins and one representing poisoned fuel pins. These two types of pins were differentiated because of the differences in thermal performance that exist between fuel pins that use burnable absorbers and pins of uranium fuel only.

Figure 1-2: Envelope Pin Profile for the Case Study BWR Extended Cycle Core



The envelopes for the extended cycle BWR and PWR are shown in Figures 1-2 and 1-3. The pin power (linear heat generation rate - LHGR) is measured relative to the core average LHGR, i.e. relative power fraction, and is plotted as a function of pin burnup. Not shown in the interest of visual clarity, the envelopes in Figures 1-2 and 1-3, are conglomerates of those of many different pins. While individual pins contribute to the envelope pin profile for as many as 15 timesteps for the case study PWR (Figure 1-3), the envelopes shown in Figure 1-2 represent a different pin at each timestep (these effects are not shown graphically in the interest of visual clarity. This difference between the PWR and BWR can be accounted for by (1) the fact that there are more fuel pins in the BWR and consequently more discrete locations at which the peak pin could be and (2) the BWR core uses control rod movement to control power shapes during operations which may shift the peak power around more than the PWR model, which withdraws control rods completely during operation.

Figure 1-3: Envelope Pin Profile for the Case Study PWR Extended Cycle Core



From Figures 1-2 and 1-3, it is apparent that the unpoisoned envelope pins burn at higher (relative) powers for a longer period of time (than the unpoisoned pins which burn at consistently lower powers throughout pin life) in both the case study BWR and PWR. The higher powers of the unpoisoned pins is due mainly to the fact that the burnable absorbers in the poisoned pins absorb the neutrons that would otherwise cause fission, lowering the power generated in these rods. The lower burnup of the poisoned pins can also be explained by the parasitic effect of the burnable absorbers; since less fissions are happening in these pins, they are less burned. Consequently, since many of the potential fuel performance problems are temperature (power) driven, unpoisoned pins may pose more of a problem since they burn longer and consistently hotter than their poisoned counterparts.

The changing peak pin location and power present challenges for the reference cycle cases as well. Assuming the reference cycles to be at or near equilibrium, the hottest pin at each burnup step was tracked for each batch of the reference cycles. The relative powers were then plotted over the range of burnup for all batches to create the envelope pin, shown in Figures 1-4 and 1-5 for the case study BWR and PWR. Data points that fell below these envelopes were not used since they did not present as great of a challenge to fuel performance as those on the envelope, illustrated in Figure 1-5.

Additionally, the same envelope is used for both poisoned and unpoisoned pins for the PWR reference cycle, because of limited information availability. Given that unpoisoned pins will burn hotter for longer periods of time than poisoned pins, the envelope in Figure 1-5 most likely represents the unpoisoned envelope pin. This means that using this envelope for the poisoned pin will yield quite conservative results.

Figure 1-4: Envelope Pin Profiles for the Case Study BWR Reference Cycle Core

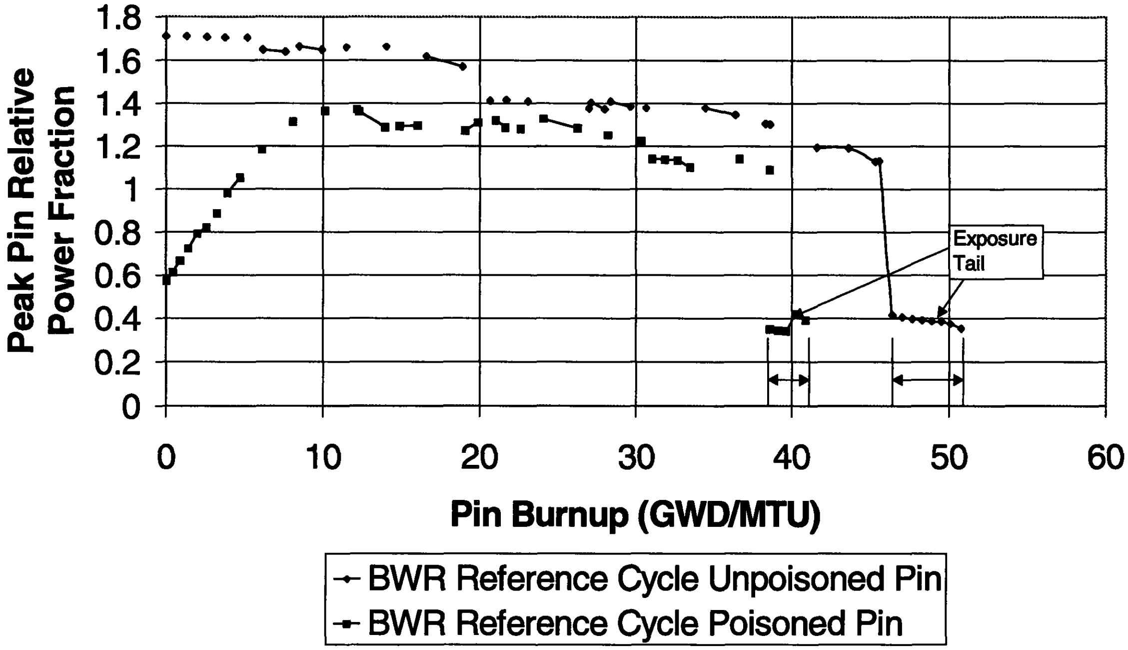
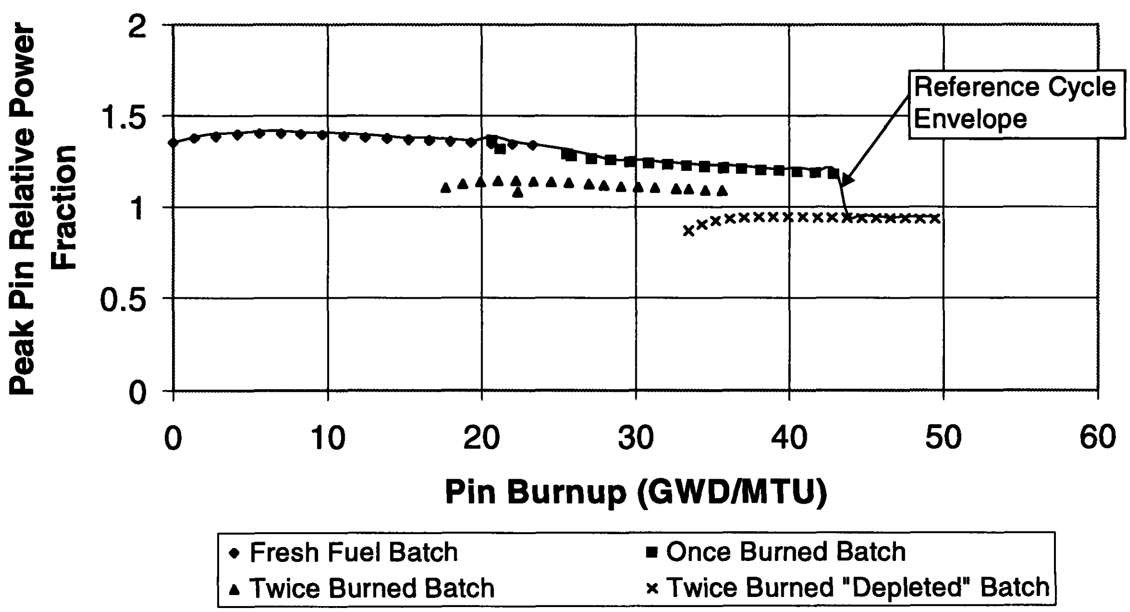
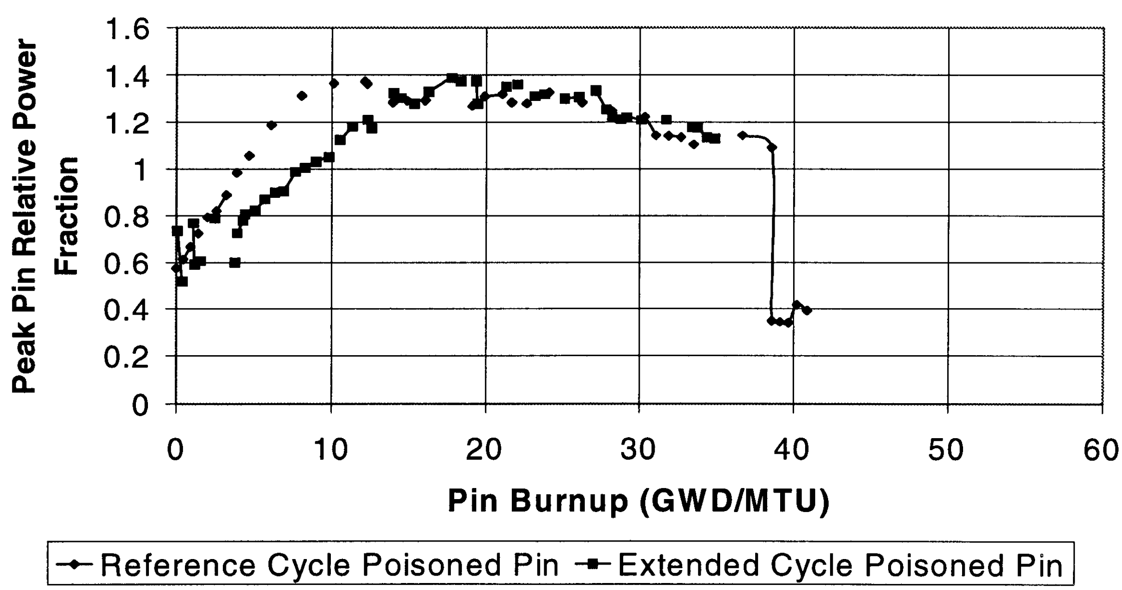


Figure 1-5: Envelope Pin Profile for the Case Study PWR Reference Cycle Core



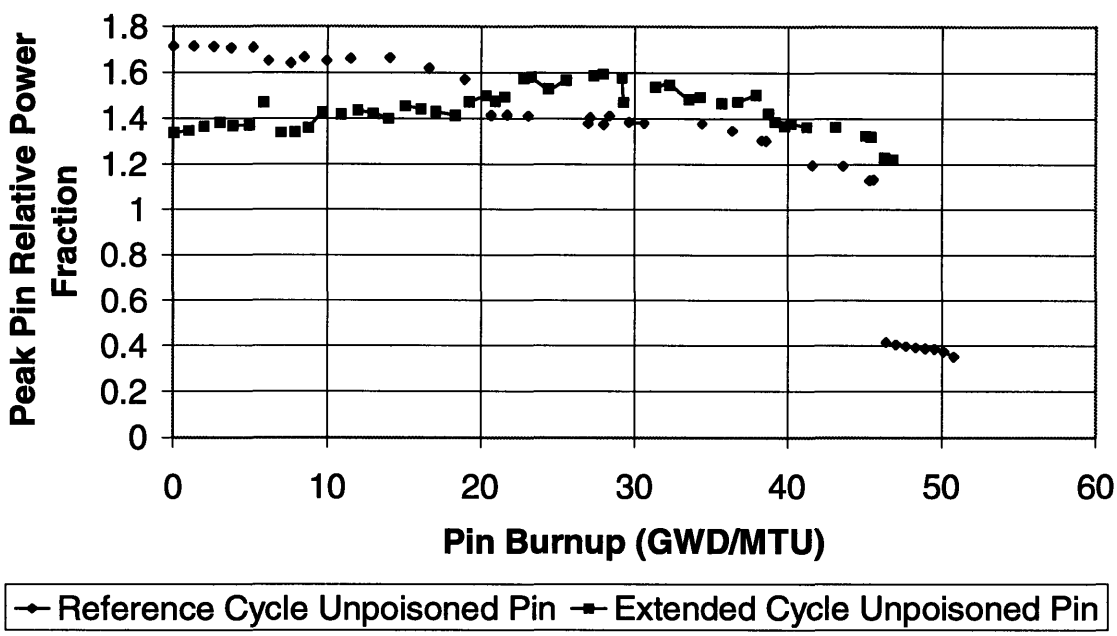
The envelope pins generated in this section are invaluable tools that are used as the basis for evaluation of extended cycle fuel performance, through both direct assessment using computer codes and comparative assessment against the chosen reference cycles. Figure 1-6 shows that the extended cycle poisoned envelope pin for the case study BWR operates at powers less than or comparable to the reference cycle pin; the difference at the beginning of pin life is due mainly to the higher burnable poison loading of the extended cycle pin and the accompanying increase in neutron parasitic effect. Coupled with the fact that the actual in-core residence time for an extended cycle pin is considerably less than that of the reference cycle (48 calendar months v. 72 calendar months), this indicates that most fuel performance issues for these pins should not be a problem. The special thermal concerns associated with different burnable absorbers, however, may create unique problems for these pins, the effects of which will be discussed in the next chapter.

Figure 1-6: Comparison of Poisoned Envelope Pin Profiles for the Case Study BWR



The comparison for the unpoisoned envelope pins for the case study BWR, made in Figure 1-7, also shows that fuel performance issues may not be exacerbated by extended cycle operation since the extended cycle pin operates at powers comparable to those of the reference cycle pin over pin-life. While the extended cycle pin does operate at powers marginally above the reference cycle pin near end of pin life, the reference cycle pin burns longer and has a longer in-core residence time.

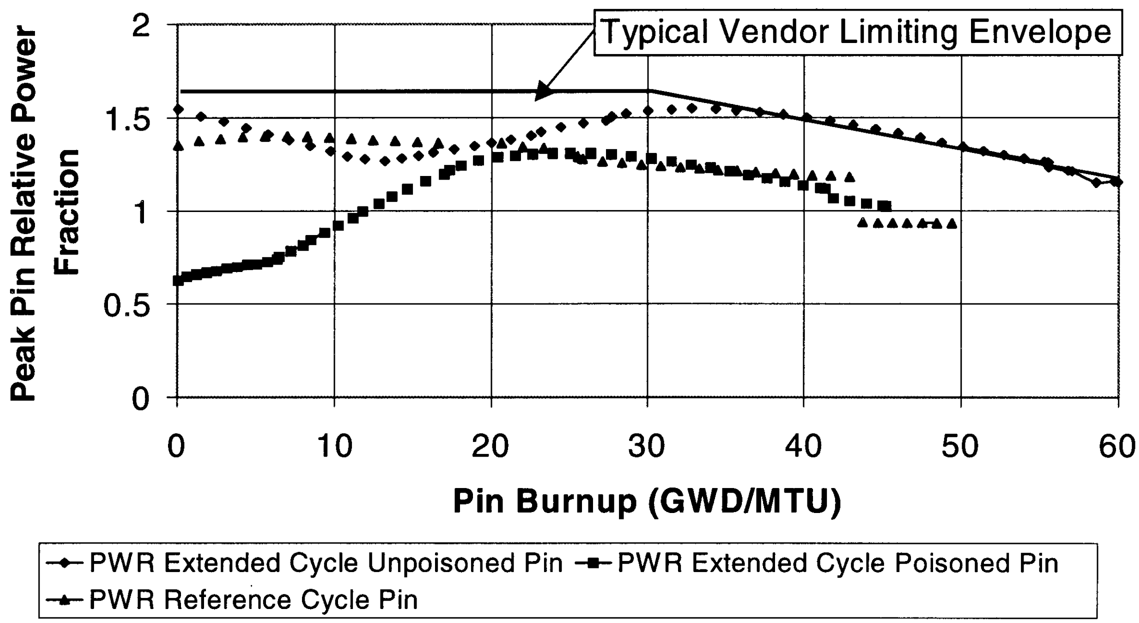
Figure 1-7: Comparison of Unpoisoned Envelope Pin Profiles for the Case Study BWR



For the case study PWR in Figure 1-8, similar results are found to those for the BWR for the envelope poisoned pin. The extended cycle pin operates at powers either less than or approximately equal to those of the reference cycle, again indicating that some of the fuel performance issues for these pins should not be a problem. The unpoisoned extended cycle envelope pin operates close to the reference cycle envelope pin power near the beginning of pin life but operates at much higher powers later in life

(>20 GWD/MTU), exceeding what is believed to be a typical envelope for this kind of fuel. From these two comparisons, it is apparent that the extended cycle unpoisoned pins may challenge barriers to technical feasibility for extended operating cycles in the case study PWR, the extent of which will be evaluated in the next chapter.

Figure 1-8: Comparison of Envelope Pin Powers Over Pin Life for the Case Study PWR



1.4 Issues unique to extending operating cycles

Central to the fuel performance challenges that will be faced by extended operating cycles is that fuel will be in one location in the reactor core for a longer period of time than normal. Consequently, fuel in higher power regions of the core would be burned at high temperatures for a longer period of time than with current operating strategies, which use refueling outages to shuffle fuel to prevent this problem. Multi-batch cores also use fuel with varying enrichment to control power distributions; thus fuel inherently sees lower power later in life, even in the same location. Additionally, fuel is not rotated in an extended operating cycle as often as it is in current practice, subjecting some assemblies, especially peripheral ones, to flux gradients for a longer period of time. Since most fuel performance phenomena are driven by temperature or flux gradients, significant barriers may exist to the technical feasibility of extended operating cycles.

Extended *cycle* operations should not be confused with extended *burnup* operations, since the core average discharge burnup at end of full power life of both the extended and reference cases is about the same. The in-core residence time for a fuel rod is longer in the reference cycle case, supporting the idea that the long residence time *without shuffling* is the key inherent cause of fuel performance problems for extended operating cycles.

Of the 10 steady state fuel performance criteria that the NRC has required be assessed (listed in Table 1-2), 8 of them present unique issues to extended operating cycles: (1) stress, strain, and loading limits, (2) fatigue cycling, (3) fretting, (4) oxidation, secondary hydriding, and CRUD, (5) rod bowing and axial growth, (6) rod internal pressure, (9) clad overheating, and (10) centerline melt. While a more detailed description of how these criteria are affected by extended cycles is discussed in the next chapter, the common and most basic reason is that fuel is left in one position for a longer period of time with extended operating cycles than for reference cycle operations.

Given the limited availability of fuel performance computer codes for non-commercial users, only 4 of the above factors (4,6,9,10) are evaluated quantitatively in this report. While one of these factors (9) is measured using results from the core design analysis, three of these factors (4,6,10) are assessed using a state of the art code developed by Yankee Atomic Electric Company (YAEC) called FROSSTEY-2 (Fuel

ROd **S**teady-**S**tate **T**hermal **E**ffects - see Appendix A for an explanation of the integrated process that yielded the assessment of these three factors) [M2]. This licensing level code can be used to predict most fuel rod thermal parameters during steady state operation including rod internal pressures, rod temperature distributions, rod dimensional changes, and fuel-to-rod gap conductance [S2]. EPRI's code ESCORE or Siemens' RODEX are other computer codes that will evaluate these four factors as well as the others listed previously.

While tools may not be available to address the other four relevant factors (1,2,3,5) quantitatively in this report, the rod temperatures, pressures and dimensional changes that can be obtained from FROSSTEY-2 will help in these evaluations. Additionally, given knowledge of the mechanisms underlying these other four factors, a qualitative assessment of how extended operating cycles will affect them can be made.

1.5 Issues common to all operating cycles

For the sake of completeness, the two criteria that the NRC requires to be evaluated for fuel performance that are not a factor in extended cycle operations are discussed. The first, primary hydriding, is centered around the level of moisture and other hydrogenous impurities inside the fuel rod during fabrication. This is a concern because of the reaction between moisture and the inner surface of the fuel rod which can cause hydrogen to be picked up by the zircaloy cladding, reducing the ductility and hence, structural integrity of the fuel rod. This effect is similar to the secondary hydriding effect resulting from the corrosion of the Zircaloy discussed in the next chapter, except the higher pressures that can exist within the fuel rod will accelerate hydrogen pickup.

Since pure zirconium is very reactive with water at high temperatures and pressures, primary hydriding is especially of concern in some BWR fuel which uses a thin layer of pure zirconium on the inside of the fuel to act as a "sponge" for fuel pellet cladding mechanical interaction (PCMI). However, innovations such as General Electric's Tri-Clad©, which uses a thin layer of Zircaloy on top of the pure zirconium to impede primary hydriding, address this concern for BWR fuel. While primary hydriding is certainly a concern for nuclear fuel performance, it is a manufacturing issue, an area that is not affected by the cycle length at which a plant is operated.

Cladding collapse is the other fuel performance issue that is not affected by extended cycle operations. If axial gaps in the fuel pellet column occur due to densification, cladding has the potential of collapsing into these gaps. Because of the large local strains accompanying this phenomenon, collapsed cladding is assumed to fail. Consequently, prevention of this fuel failure mechanism may lie in preventing axial gap formation. Since fuel densification is complete early in fuel rod life, extending the length at which these fuel rods operate in one position has no effect on this factor [E1]. Like primary hydriding, this criterion could have more severe consequences for extended operating cycles should it cause fuel failures; however, extended operating cycles do not enhance these effects.

1.6 Plant specific factors

Given the differences in the ways that BWRs and PWRs are designed and operated, certain fuel performance factors will be more troublesome for each type of plant. Of those that are being considered in this report, only two are predicted to cause more problems for BWRs, (1) stress, strain, and loading limits, and (2) fatigue, while one is hypothesized to be of greater concern for PWRS, (3) fretting. The increased problems for BWRs with respect to (1) and (2) are both related to the fact that there are more power ramps of large magnitude that BWR fuel experiences during operation. These power ramps result from the fact that every time that control rods are moved during operation, the power level is first lowered, then raised. The power up-ramps cause the fuel to grow more rapidly than the cladding and as a result, there are an increased number of mechanical cycles on the cladding from the force of the fuel and more stress on the cladding in the circumferential (hoop) direction. PWRs, which typically withdraw their control rods at the beginning of operation, don't use them during life to control power, and run at as close to full power as possible throughout cycle life, do not have this added stress or cycling effect.

With respect to fretting, PWRs may be worse off as they operate with higher flow velocities in the core subchannels. This pertains to grid-to-rod fretting only, which results from the degradation the fuel rod experiences from rubbing against the fuel assembly grid due to hydraulic forces. Since the other kind of fretting, debris fretting, is a function of the amount of debris introduced into the coolant, neither type of LWR has a distinct advantage.

1.7 Summary

Among the relevant steady state fuel performance criteria outlined by the NRC's Standard Review Plan, eight of these factors may be exacerbated by extended cycle operation. The concern with respect to these factors centers around the idea that fuel in extended operating cycles will be in one place for an extended period of time without the benefit of replacement, shuffling, or rotation, causing pins in high power regions of the core to burn hotter for long periods of time. A method for quantifying these factors was proposed by creating an "envelope" pin, whose operating characteristics represented those of the peak pin within the core at each time step. Assessment of these fuel performance criteria as well as solutions to barriers to technical feasibility of extended cycle operations are a key element of successful implementation of this new operating strategy.

CHAPTER 2: ANALYSIS OF EXTENDED CYCLE FUEL PERFORMANCE ISSUES

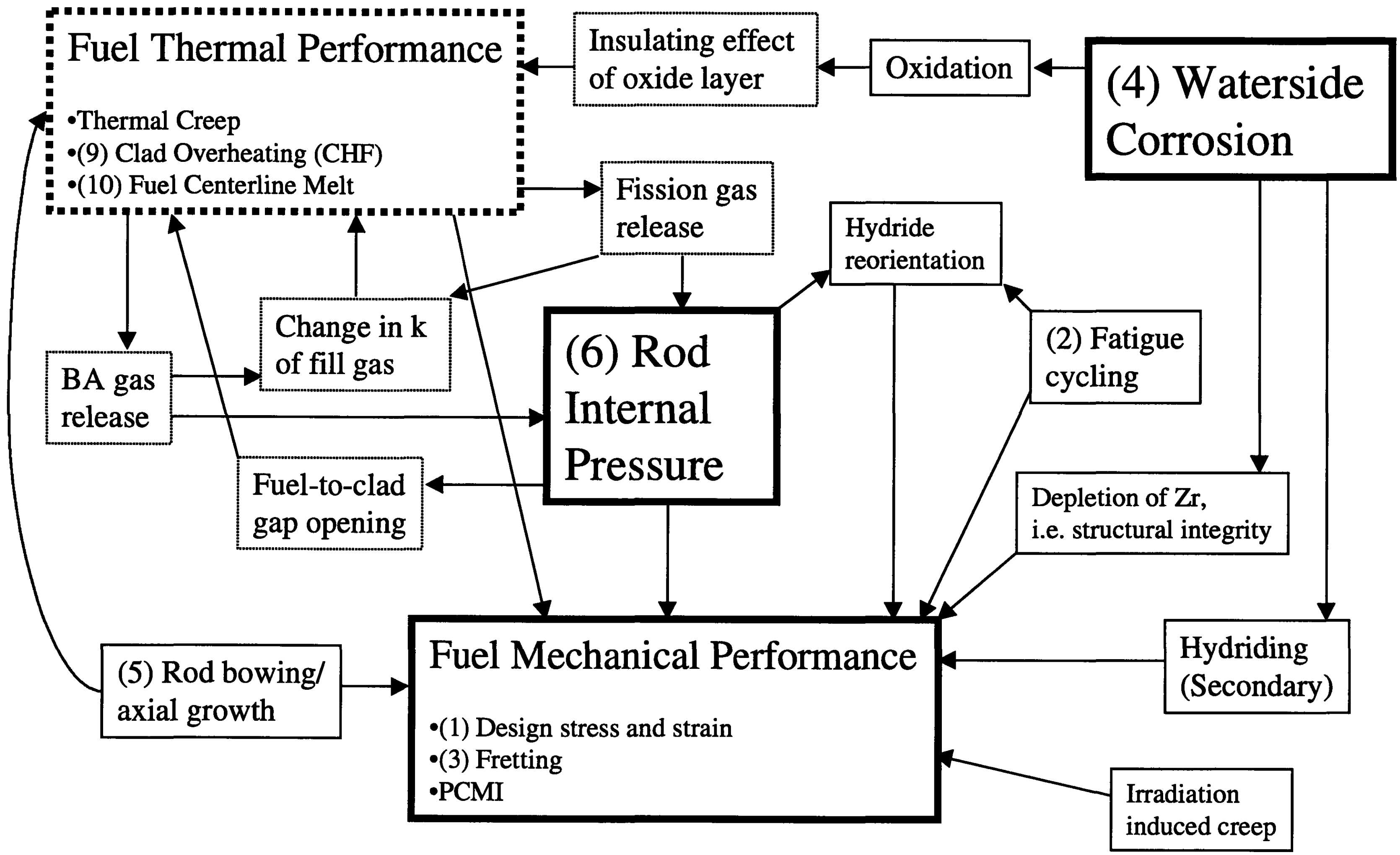
2.1 Introduction

Given the list of fuel performance issues that may be exacerbated by extended cycle operation, a comprehensive evaluation of these issues follows. Whether or not these issues pose barriers to technical feasibility will be determined. Should an issue be found troublesome, solutions to overcome this obstacle to implementing extended operating cycles will be offered.

This assessment will be both quantitative and qualitative. Where quantitative, the envelope pin discussed in Section 1.3 will be used as the fuel pin that is being evaluated. When issues are discussed in a qualitative sense, review of existing literature on the respective topic as well as personal insight from industry and academic experts will be used as the basis.

With the exception of (3) fretting, all of the fuel performance issues are inter-related; that is, a change with respect to one issue will have an effect on another issue. This is illustrated in Figure 2-1, which shows the relationship among those steady state fuel performance issues and their contributing factors that are thermal (denoted by the boxes with the dashed outline) and those that are mechanical (denoted by the boxes with the solid outline). Further, it can be seen that all of the fuel performance issues associated with implementing extended operating cycles rest on four cornerstones: fuel thermal performance, waterside corrosion, rod internal pressure, and fuel mechanical performance. These issues, their inter-relationships, and their associated contributing factors will be explored in this chapter.

Figure 2-1: Steady State Fuel Performance Issues that May Be Affected Uniquely by Extended Operating Cycles



2.2 Fuel thermal performance

2.2.1 Clad overheating (Critical Heat Flux (CHF))

In an effort to prevent fuel rod failure due to overheating of the cladding, the Critical Heat Flux (CHF) criterion is used in LWRs to predict when a boiling crisis will occur. In both BWRs and PWRs, this crisis occurs when too much heat is being added to the coolant subchannel and transition from one boiling regime to another results. For BWR's, this crisis occurs when the liquid in the two-phase water-steam mixture no longer blankets the fuel cladding and is only found as droplets in the vapor, i.e. mist flow. This liquid-rich vapor does not carry away heat as well as the liquid blanket/steam two-phase mixture, increasing the temperature of the cladding and fuel. Additionally, the point at which the two-phase mixture ends and the one-phase steam flow begins will oscillate along a small length of the cladding, which will lead to thermal fatigue, a condition that will eventually fail the clad. This phenomenon is known as dryout.

For PWRs, the boiling crisis occurs when so much heat is being added to the channel, i.e. the heat flux reaches the critical point, such that the water in the subchannel departs from nucleate boiling and forms a thin, insulating layer of vapor along the cladding outer wall. This insulating layer is dangerous because it can raise the temperatures of the cladding and fuel dramatically, increase the rod internal pressures, and weaken the structural integrity of the clad. These temperatures can rise so significantly that the temperature at the clad-oxide layer interface reaches a point where the oxidation process becomes autocatalytic, sending corrosion of the cladding out of control and breaching the fuel rod. Since some of the extended operating cycle envelope pins operate at higher Linear Heat Generation Rates (LHGRs) and consequently add more heat to the sub-channel than with current operations, critical heat flux is a criterion that must be assessed when evaluating this new operating strategy.

For the BWR, there are five parameters that must be examined in order to determine when CHF will occur; for the PWR, there are six. These are listed below in Table 2-1 [T1]:

Table 2-1: Parameters for Determining if CHF is Predicted to Occur

BWR	PWR
Inlet enthalpy	Local enthalpy
Channel length	Length of channel at boiling crisis
System pressure	System pressure
Mass flux	Mass flux
Channel equivalent diameter	Channel equivalent diameter
	A factor for a non-uniform flux distribution (F_C)

While none of the factors listed above will change with extended operating cycles in BWRs and only 1 may change for PWRs (length of channel at boiling crisis), it is also important to consider the heat flux distribution that can be expected within an extended cycle core. Since extended operating cycles change the power distribution within the core, the Minimum CHF Ratio (MCHFR) or the minimum value of the ratio between the critical heat flux and the heat flux that exists in a sub-channel will undoubtedly change both in value and location. MCHFR needs to be considered since it is the key determinant in whether or not a boiling crisis will occur for a given core design. However, the change in MCHFR comes about from a change in the CHF due to a different power distribution. Thus, the MCHFR issue becomes a neutronic design issue. Since the same type of fuel is being used in both the reference and extended cycle LWRs, and the extended cycle power distributions, i.e. peaking factors, are within the design limits, the change in power distribution is not significant enough to result in a boiling crisis [M2, H2].

By staying within the neutronic design envelopes for peaking factors, CHF is avoided and overheating the cladding is not a concern for steady state operations of the extended cycle core designs presented for the case study LWRs in Ref. [M2]. Additionally, the margin available for transient effects with respect to this parameter in the BWR extended cycle core design may be better than for the reference cycle core, since the design power distribution against which the former core is designed is for a BWR/5 loaded with 8x8 fuel assemblies and the latter is designed against Siemen's Atrium-10 design power distributions. While both cores use an improved 10x10 lattice which offers increased margins to core thermal limits, the extended cycle core was designed against more restrictive set of neutronic parameters, potentially giving it a larger amount of conservatism, hence thermal margin for transient effects. Since a completely technically feasible reference cycle core for the case study BWR could not be established due to lack of information availability, the effect of this design conservatism (for the extended cycle core) could not be assessed on a comparative basis. However, information available from the reference cycle core for the case study PWR indicates that the extended cycle core design degrades the thermal margin for CHF (in the unpoisoned pins), throughout most of core life, shown in Figure 1-8. Whether or not this degradation is significant enough to have adverse consequences in the case study PWR or if an advantage exists in the case study BWR extended cycle core design needs to be addressed in a transient analysis.

2.2.2 Fuel centerline temperature

Given that some fuel pins will be operating at higher powers when higher burnup is achieved than with current practice and that the melting point of UO_2 degrades with burnup, extended operating cycles have the potential to pose problems with respect to centerline melting of the fuel. Fuel centerline melt is undesirable because should it occur, it would cause the fuel to expand. This would not only exert an additional force on the cladding, contributing to the already existing stresses, but would also create a hot-spot on the inside of the cladding due to the high temperature of the fuel. This hot spot would create both thermal and mechanical problems and could ultimately contribute to cladding failure. This criterion is evaluated at the center line of the fuel pellet because this is the first place that fuel would begin to melt, given that the highest fuel temperatures occur here. Additionally, the centerline temperatures at the highest power, i.e. "peak", axial node are used as a means for comparison for this parameter since this is the first place where centerline melt would occur in a fuel pin.

Consistent with the comparison between the envelope pin profiles in Figure 1-6 and 1-7, Figures 2-2 and 2-3 both show the BWR reference and extended cycle envelope pins with comparable centerline temperatures over pin life. The reference cycle envelope pins have slightly higher temperatures at the beginning of pin life and the extended cycle envelope pins have slightly higher temperatures at end of life. Both are well below the melting point of the fuel throughout the life of the pin and provide a significant margin, with respect to this parameter, for security against the deleterious thermal effects which accompany a transient.

Figure 2-2: Comparison of Fuel Centerline Temperatures Between the Extended and Reference Cycle Unpoisoned Envelope Pins for the Case Study BWR

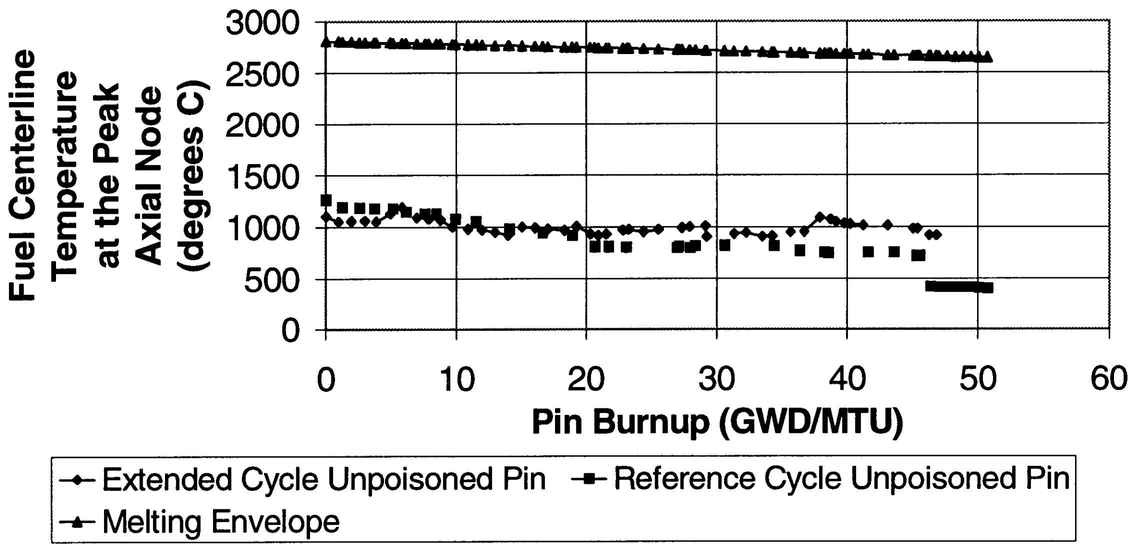
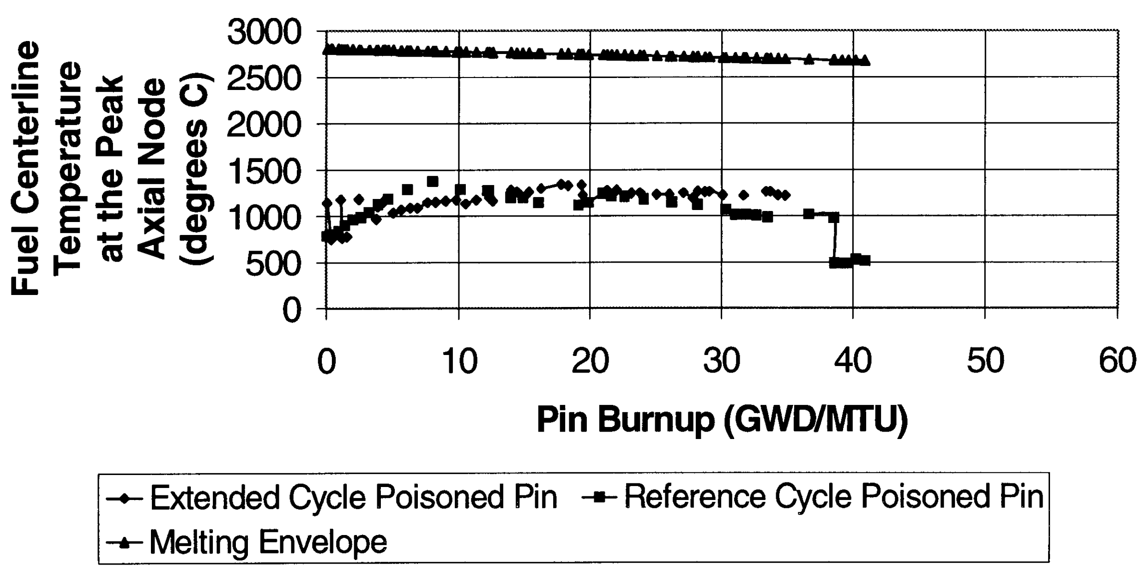


Figure 2-3: Comparison of Fuel Centerline Temperatures Between the Extended and Reference Cycle Poisoned Envelope Pins for the Case Study BWR



The temperature at which the fuel (UO_2) melts is a function of burnup and is determined by the following relationship [S2]:

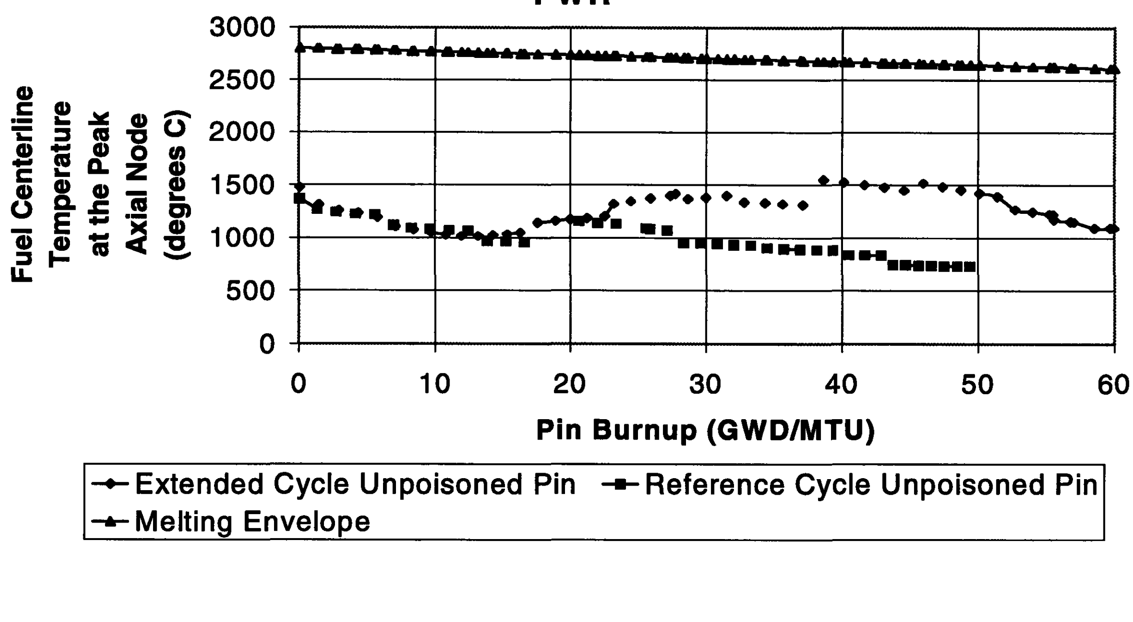
$$T_{melt}(B) = 2805^{o}C - 32^{o}C\left(\frac{B}{10\frac{GWD}{MTU}}\right) \qquad \{2\text{-}1\}$$

where: B = fuel pin exposure in GWD/MTU

The centerline temperatures for the PWR unpoisoned envelope pins (shown in Figure 2-4) also mimic the relationship shown by their respective envelope pin profiles in Figure 1-8. While the extended cycle unpoisoned envelope pin may have temperatures well above those of the reference cycle at the end of pin life, the extended cycle envelope pin is well below the melting envelope, satisfying the prescribed no-melt criterion and providing adequate margin for transient conditions.

While the centerline temperature at the peak node has mimicked all of the envelope pin profiles developed in Chapter 1 for all of the cases considered so far, this is not the case

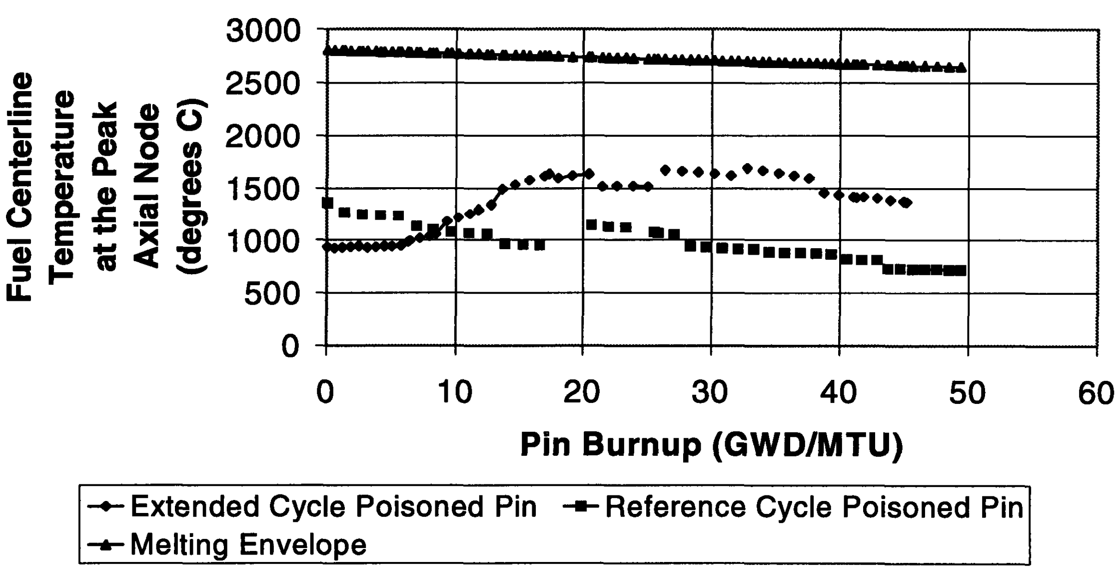
Figure 2-4: Comparison of Fuel Centerline Temperatures Between the Extended and Reference Cycle Unpoisoned Envelope Pins for the Case Study PWR



for the extended cycle poisoned pin, shown in Figure 2-5. This can be attributed to the combination of high burnable poison loading necessary to control the increased reactivity and the higher powers (LHGRs) at which PWRs operate; the latter reason distinguishes why this behavior was not seen for the BWR envelope poison pin. Again, even though the extended cycle poisoned pin has centerline temperatures well above those of the reference cycle for most of pin life, these temperatures are well below the melting envelope, providing adequate margin for transient conditions.

From the results, it is clear that the no centerline melt criterion has been satisfied and this parameter is no longer a concern. However, the higher temperatures that the PWR extended cycle envelope pins consistently face will have implications for other fuel performance issues, such as corrosion and rod internal pressure.

Figure 2-5: Comparison of Fuel Centerline Temperatures Between the Extended and Reference Cycle Poisoned Envelope Pins for the Case Study PWR



2.3 Waterside corrosion and water chemistry

Waterside corrosion is mainly a temperature driven process which is heavily dependent upon water chemistry control. Zircaloy, an alloy which is composed mainly of zirconium and is generally used as the cladding for LWRs, undergoes the following reaction with water at the operating temperatures (250-350°C) and pressures (1000 psia-2250 psia) found in LWRs:

$$Zr + 2H_2O \rightarrow ZrO_2 + 2(1-x)H_2 \uparrow + 4xH \qquad \{2\text{-}2\}$$

where the reagents represent the Zircaloy cladding (Zr), and water (coolant); and the products represent the zirconium oxide layer formed on the outside of the fuel (ZrO_2), the hydrogen gas released into the reactor coolant system, and the hydrogen picked up by the cladding (H), respectively; x in this case represents the fraction of hydrogen picked up by the cladding and is typically represented by values between 0.1 and 0.15 [M3,C1]. Both of the undesirable products of this reaction, ZrO_2 and H, are hypothesized to be enhanced by operating at longer cycle lengths. This is because the fuel will be in-core without the opportunity for shuffling for longer periods of time than with current practice, causing it to be operated at higher powers for long periods of time. However, the total in-core residence time during operation for extended cycle fuel is less than that of current practice (45 v. 49.5 and 38.8 v. 44.4 EFPM for the case study BWR and PWR[1]; the effects of outages are not accounted for in the envelope pin method used as a basis for comparison during this report; however, these effects are negligible since the

[1] Note that the values for the reference cycle cases are inconsistent with those presented in Table 1-1. This is due to limitations in (proprietary) information availability for the reference cycle neutronic models. The values listed here are the values actually used in the quantitative analysis performed in this chapter; the values listed in Table 1-1 are consistent with the analyses performed in Refs. [H1] and [M2].

temperatures, hence corrosion rates, during this time are significantly less than those experienced during operation), which may mitigate some of the harmful effects of operating at elevated temperatures for long periods of time for extended operating cycles. Waterside corrosion, which is judged to be the greatest limiting factor to implementing extended operating cycles, will be the focus of this section, which discusses its mechanisms and the use of water chemistry to help control it.

2.3.1 Oxide Layer Formation

In order to better understand how extended operating cycles will affect oxide layer thickness, an understanding of the mechanism by which this oxide layer is formed is necessary. The formation of the oxide layer has two distinct phases (separated by a discrete transition point), each with a different rate of growth, but both governed by a time-dependent (dt) Arrhenius-like relationship between the oxide-cladding interface (absolute) temperature (T) and oxide layer thickness (z), i.e. $\frac{dz}{dt} = Ae^{-\left(\frac{B}{T}\right)}$(where A and B are empirically determined functions of local variables; fast flux effects on oxide growth are ignored in this analysis, since this parameter remains relatively constant for both reference and extended cycle operations). Both phases, pre-transition and post-transition, are defined relative to the thickness at which the transition occurs. In the pre-transition phase, the oxide layer thickness approximates a cubic function and is dependent upon the Arrhenius-like relationship between z, T, and Δt; the temperature at the outer surface of the oxide; and the initial thickness of the cladding oxide layer (z_o). This pre-transition growth occurs until the transition thickness, z_{tran}, is reached, which depends only on the Arrhenius-like relationship between z_{tran} and T. Once this transition thickness is reached (typically 1.9 microns), then a closely linear post-transition growth begins, which is dependent upon the same factors as the pre-transition phase (as well as z_{tran} if $z_o < z_{tran}$), except in a different relationship [S2]. Since the transition point will occur early in core life, it is the post-transition growth of oxide layer that is of concern. Specifically, the dependence on time at temperature and fuel rod temperatures raise concerns for extended cycle fuel performance.

While the USNRC SRP is vague on what defines a suitable limit for oxide layer thickness during steady state conditions, i.e. "oxidation...should be limited," other criteria can be used to determine what a suitable limit is for this factor. Given that the USNRC SRP defines a limit for oxide thickness at 17% of the cladding thickness during accident (LOCA) conditions and that oxide layer growth is history dependent, a steady state limit should provide an appreciable margin with respect to this criterion. For the fuel used in both the case study BWR and PWR this 17% limit lies around 200 microns. Limiting the oxide buildup in steady state to 7% of the clad thickness keeps oxide layer thicknesses around 80 microns, which is around the thickness at which the oxides typically begin to spall. Thus, 7% of the cladding thickness (80 microns) will be established as the metric that will be used to evaluate oxide layer growth under steady state conditions.

Formation of an oxide layer is a concern for several reasons. First, it serves to weaken the structural integrity of the cladding by depleting zirconium to form a weaker, ZrO_2 layer. It also creates an insulated region around the cladding which drives up the temperatures across the fuel. As this temperature increases, so does the corrosion process, creating a positive feedback mechanism. The effects of this self-sustaining phenomenon, however, are mitigated by the fact that the thicker that this oxide layer becomes, the more material that the reactive ions that form these corrosion products must diffuse through. While this does slow down corrosion, the process is more heavily dependent upon temperature and these mitigating effects are less significant by comparison. Finally, once this oxide layer reaches between 70-100 microns, it may detach from the cladding or spall. This is a concern because: (1) part of the cladding has been removed and structural integrity weakened, (2) the protective barrier for ion transfer has been removed and fresh Zircaloy is exposed directly to the corrosive agent, i.e. water or steam, (3) spalled oxide can build up, block flow, and decrease heat transfer from the fuel to the coolant, and (4) spalled material typically becomes activated and will increase the radiation fields around the primary coolant system. A more quantitative analysis of this factor will be performed in the next section.

2.3.2 Secondary hydriding

Again, an introduction to the mechanism behind secondary hydriding of Zircaloy cladding is necessary to understand how extended operating cycles will influence this effect. This factor is of concern because hydrides within Zircaloy cladding can decrease the ductility of the cladding and thus weaken the overall structural integrity. Additionally, since this criterion is dependent upon both temperature and factors that contribute to cladding stress, extended cycle operation could have a significant effect in this area.

The process of cladding hydriding takes place in four steps: hydrogen pick-up, distribution, precipitation, and re-orientation. The hydrogen pick-up stage is relatively simple, well understood, and is described in Equation 2-2. Exactly how this hydrogen is distributed throughout the cladding and when it will precipitate to form the harmful hydrides is not as well understood and has been under investigation over the past four decades. However, for the purposes of this report, a general understanding of this phenomenon will be sufficient. Under the influence of a temperature gradient, hydrogen in Zircaloy will tend to move to the colder regions until a steady state distribution of hydrogen in solution is attained [S3]. It is in these colder regions that the hydrogen will precipitate, forming needles or platelets that are very brittle, do not bond to the surrounding zirconium, and have almost no strength. The phase, size, and orientation of the zirconium hydrides, all of which determine the weakening effect of the hydrides, depend on the hydrogen concentration, the cooling rate, the present stresses, and the microstructure of the Zircaloy [N2]. While the size and phase of the platelets is somewhat of a concern, their orientation has a much more significant effect, as platelets that are oriented radially (or normal to the primary hoop stress) will weaken the cladding appreciably. Large stresses and fatigue cycling of the cladding cause hydride reorientation in the radial direction.

Given that all four phases of the hydriding process are dependent upon how much hydrogen is picked up from the cladding, extended operating cycles may be worse than current practice in this respect, as some of the fuel will run at higher temperatures for longer. However, the solubility of hydrogen in Zircaloy is also temperature dependent, as the higher the temperature of the cladding, the greater the solubility limit, i.e. less hydrogen precipitates. Since the hydrogen has to precipitate in order to weaken the cladding both directly and via reorientation, extended cycles may be better off during operation (at 100% power) with respect to this parameter. Additionally, the shorter cumulative in-core residence time of extended cycle fuel may also mitigate the negative effects of the higher temperatures they experience with respect to cladding hydrogen pick-up. The trade-off between in-core residence time, increased solubility, and greater hydrogen pick-up at higher temperatures needs to be evaluated to determine if extended cycles are indeed better or worse off in this respect.

However, given a decrease in power level, such as during control rod movement in BWRs, or shut down for a forced or refueling outage in both kinds of LWRs, more hydrides are likely to precipitate in extended cycle fuel, given that more hydrogen has been picked up. The rate at which the power drops, i.e. the rate at which the cladding cools, will affect the size of the hydrogen platelets that are formed: slow cooling rates yield large platelets and vice versa. Additionally, both the magnitude of stresses present in the cladding and the fatigue cycling of the cladding determine to what extent the hydrides will reorient. The contributing factors to these stresses include rod internal pressure, Pellet-Clad Mechanical Interaction (PCMI), rod bowing, and thermal and irradiation induced creep. While all of these factors will be discussed in their respective subsequent sections, it can be said in general that they will all be exacerbated by extended cycle operation and consequently, so will hydride re-orientation and negative effects due to secondary hydriding.

Since the formation of the products of the corrosion reaction, oxide layer and hydrogen picked up in the cladding, are driven mainly by time and temperature (the cladding-oxide interface, i.e. cladding outside diameter, temperature), a comparative assessment of these parameters between the envelope pins of the reference and extended operating cycles would give an indication of how corrosion would be affected by the proposed operating strategy. Once again, this temperature is measured at the peak axial node, since this is the limiting value. Additionally, it should be noted that the in-core residence times that are compared are for each of the cases when they are operating, i.e. Effective Full Power Months (EFPM); the envelope pin approach developed for this report does not account for in-core residence time due to outages. However, this time is negligible with respect to the effects of corrosion since the temperatures of the fuel at this time are significantly below those achieved during operation.

For the case study BWR, Figures 2-6 and 2-7 show that the temperatures that drive the corrosion process are comparable for the reference and the extended cycle poisoned and unpoisoned pins. These results are consistent with the envelope pin profile comparisons in Figures 1-6 and 1-7. Coupled with the fact that the formation of the corrosion products is also a function of time, the longer in-core residence time for the reference cycle BWR fuel pins indicates that extended operating cycle pins may be better off with respect to this parameter.

Figure 2-6: Comparison of Corrosion Governing Temperatures for the Case Study BWR Poisoned Envelope Pins

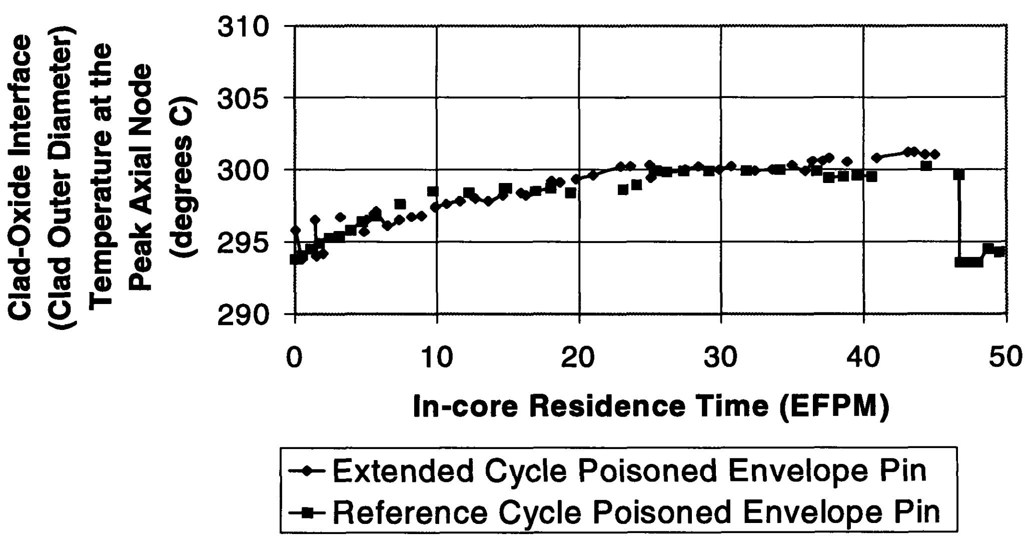
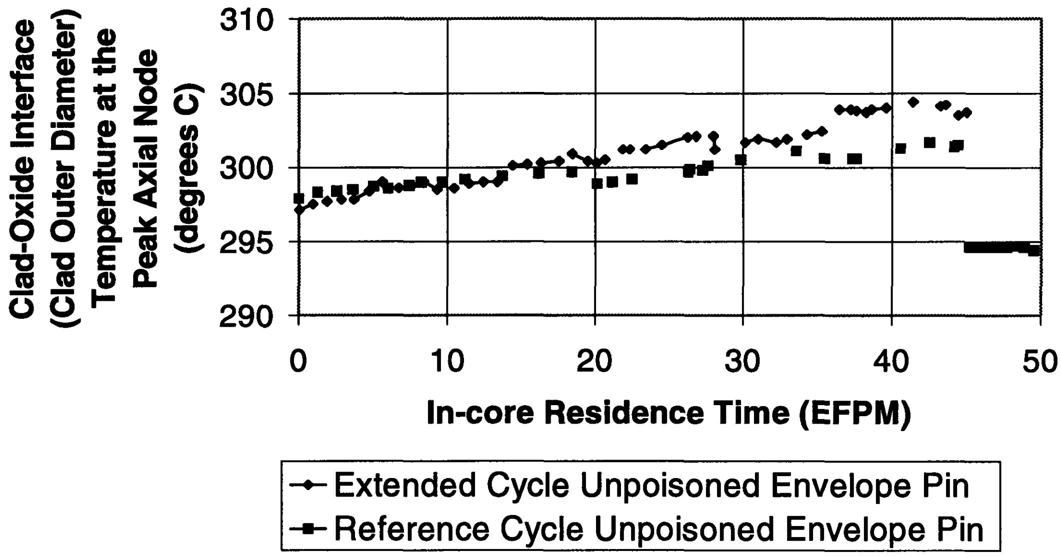


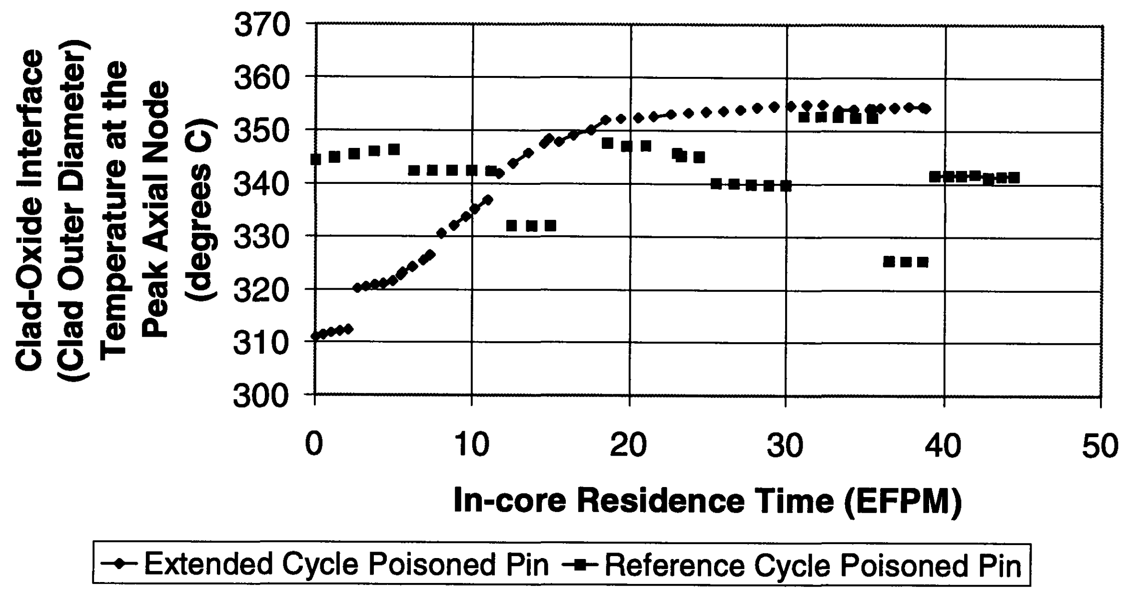
Figure 2-7: Comparison of Corrosion Governing Temperatures for the Case Study BWR Unpoisoned Envelope Pins



With respect to the case study PWR, Figure 2-8 shows that the extended cycle poisoned envelope pin has cladding-oxide interface temperatures below those of the reference cycle poisoned envelope pin early in pin life, and greater than their reference cycle counterpart later in life, showing that the extended cycle poisoned pin may be worse with respect to corrosion. However, the shorter in-core residence time experienced by the extended cycle pin may mitigate the adverse consequences of operating at a higher temperature. The extent of this trade-off needs to be examined more closely in future work.

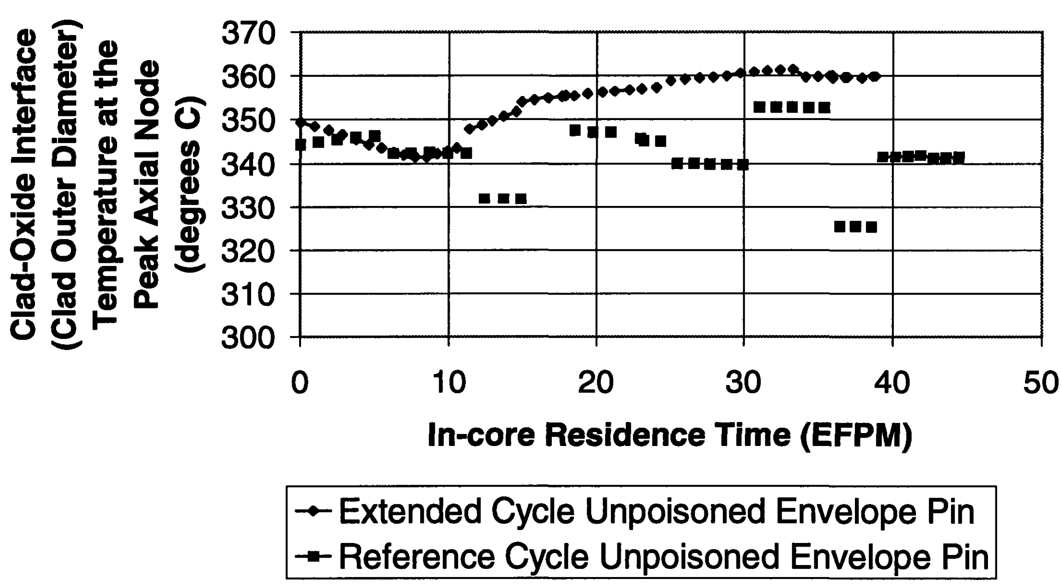
While these results are consistent with the envelope pin profile comparison (made in Figure 1-8) for the beginning of pin life, they diverge at the end of pin life. This difference between the two sets of results can be attributed to the use of gadolinia (Gd_2O_3) in only the extended cycle poisoned pins (1.0x IFBA is used in both pins), which significantly degrades the thermal conductivity of the fuel. This large difference does not exist between the extended and reference cycle poisoned pins for the case study BWR because both use Gadolinia at appreciable concentrations (7 $^{w}/_{o}$ and 12 $^{w}/_{o}$).

Figure 2-8: Comparison of Corrosion Governing Temperatures for the Case Study PWR Poisoned Envelope Pins



For the case study PWR unpoisoned envelope pins, Figure 2-9 shows that the extended cycle pin runs at consistently higher temperatures than its reference cycle counterpart, pointing to the fact that these pins may be worse with respect to corrosion. This result is consistent with the envelope pin profile comparison made in Figure 1-8. While the PWR extended cycle pins may be worse off with respect to corrosion because they run at higher temperatures, their slightly shorter cumulative in-core residence time (38.8 v. 44.4 EFPM) may mitigate these harmful effects. Additionally, should waterside corrosion be found to be a significant problem for the extended cycle PWR core, fuel assemblies with a larger number of fuel pins could be used to decrease the amount of power generated per pin and consequently, the higher fuel pin temperatures that exist for the extended operating cycle. In order to implement this solution, however, the upper core internals would need to be modified and an extensive licensing and safety analysis would need to be performed, resulting in an additional cost. A more generic solution to the corrosion-related problems associated with extended cycle operation is the development of improved cladding alloys; this solution, however, is both expensive and time consuming. Yet another solution that could be implemented would be to use annular fuel pellets, which would decrease the temperatures that drive the corrosion process. However, this solution would require either a higher enrichment to maintain cycle length (incurring additional costs and neutronic design problems) or a penalty in operating cycle length, because of the mass of fuel that is removed from the pins.

Figure 2-9: Comparison of Corrosion Governing Temperatures for the Case Study PWR Unpoisoned Envelope Pins



2.3.3 Water chemistry issues

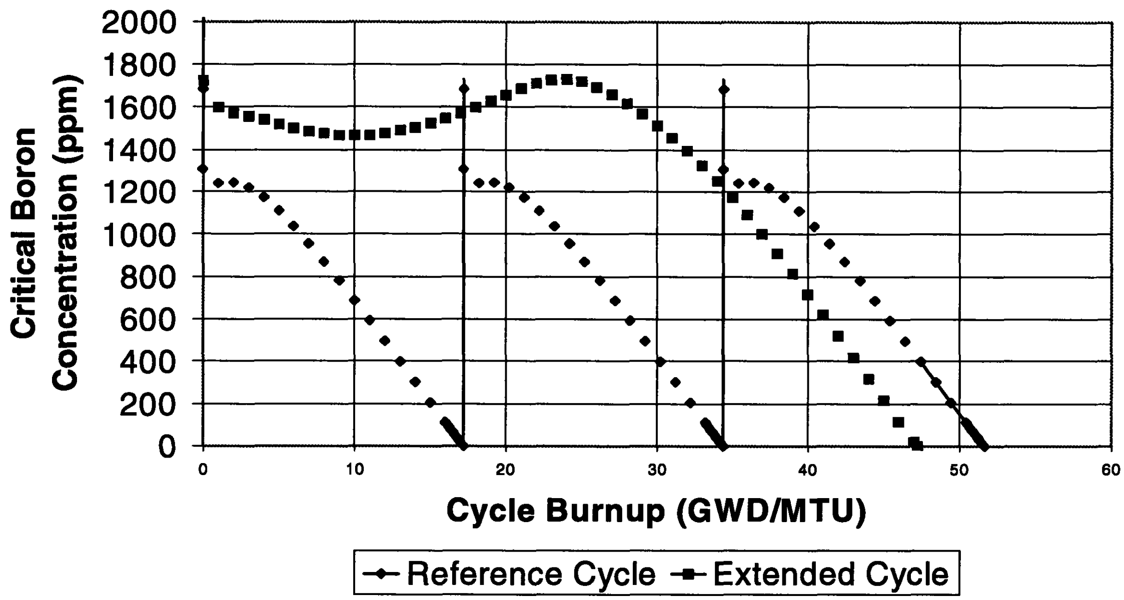
While oxide layer formation and cladding hydrogen pick-up are concerns with respect to Zircaloy waterside corrosion, other harmful effects, such as CRUD deposition and Primary Water Stress Corrosion Cracking (PWSCC), need also to be considered. Most of these factors can be mitigated or even prevented through proper water chemistry control. How extended cycles may change water chemistry operating strategies will be explored in this section.

With respect to BWR water chemistry, extended operating cycles should not have a unique effect. This is because BWR water chemistry centers around the radiolytic decomposition of water from neutron collisions. Since core neutron flux levels are comparable to those found for current practice, the rate of this decomposition should not be affected by extended cycle operation.

Since the highly purified water used in the primary coolant will radiolytically break down into its hydrogen and oxygen components over core life, many BWRs now use hydrogen water chemistry (HWC) to maintain a suitable reducing environment to mitigate PWSCC. By injecting hydrogen into the coolant, the availability of dissolved oxygen decreases, causing the radioactive nitrogen from the $O^{16}(n,p)N^{16}$ reaction in the coolant to form the volatile compounds ammonia (NH_3) and nitrous oxide (NO). With an availability of dissolved oxygen, the radioactive nitrogen will form less volatile, soluble compounds such as nitrates (NO_x). The non-volatile compounds formed as a result of excess oxygen availability are water-soluble and will consequently not pass through the steam separators nor leave the core, keeping the activity of the primary steam loop low. However, the volatile compounds that are formed when there is a decreased oxygen availability, i.e. with hydrogen injection, will pass through the steam separators and into most of the components that come into contact with the main steam. Since N^{16} is a γ-emitter with a 7.13-second half-life, the activity of the primary steam loop will consequently increase. Extended operating cycles should not increase the rate at which hydrogen needs to be injected in BWRs, keeping the radiation fields in the primary steam loop relatively the same as for current operations.

While unique effects with respect to BWR water chemistry are hypothesized not to exist for extended operating cycles, PWR water chemistry presents challenges for extended cycle implementation. Maintaining the pH of the primary coolant within acceptable levels (6.9-7.4) is one way that cladding corrosion and crud deposition concerns can be mitigated in PWRs. In general, a pH near or below the lower end of the acceptable range (6.9) may increase the amount of CRUD that is deposited on a fuel rod and a pH near or above the upper end of this range (7.4) may enhance the effects of PWSCC and the oxide layer formation rate (and consequently, the hydrogen pick-up rate). While the level of boric acid in the primary coolant is relatively fixed in a given core design for reactivity management purposes, the pH can be controlled by using lithium hydroxide (LiOH). However, the high boric acid concentrations that accompany extended cycle operation require that high levels of lithium hydroxide be used to maintain the pH within the prescribed acceptable limits. The high levels of Li (>2.2 ppm) that accompany such a strategy are suspected to be the cause of the deleterious effects on the clad experienced at pH's near or above the upper limit of the acceptable range. Additionally, higher levels of lithium (also >2.2 ppm) at other pH's within this range are believed to have the same harmful effects. While levels of boric acid could be reduced in extended cycles, it would be through an increase in the use of burnable absorbers and would be at the expense of cycle length, wasted fuel, and decreased fuel performance. Thus, the levels of boric acid for the given PWR core design, shown in Figure 2-10, should be seen as fixed.

Figure 2-10: Boron Concentration over Cycle Life for the Case Study PWR



The trade-off between the levels of lithium hydroxide, boric acid, and pH is illustrated in Figure 2-11 for the case study PWR at the coolant average temperature. Additionally, EPRI's coordinated and two modified water chemistry operating strategies are shown. These three strategies are based on EPRI's four generic recommendations for maintaining a good balance between boric acid (B), lithium hydroxide (LiOH), and pH, listed in order of priority [E2]:

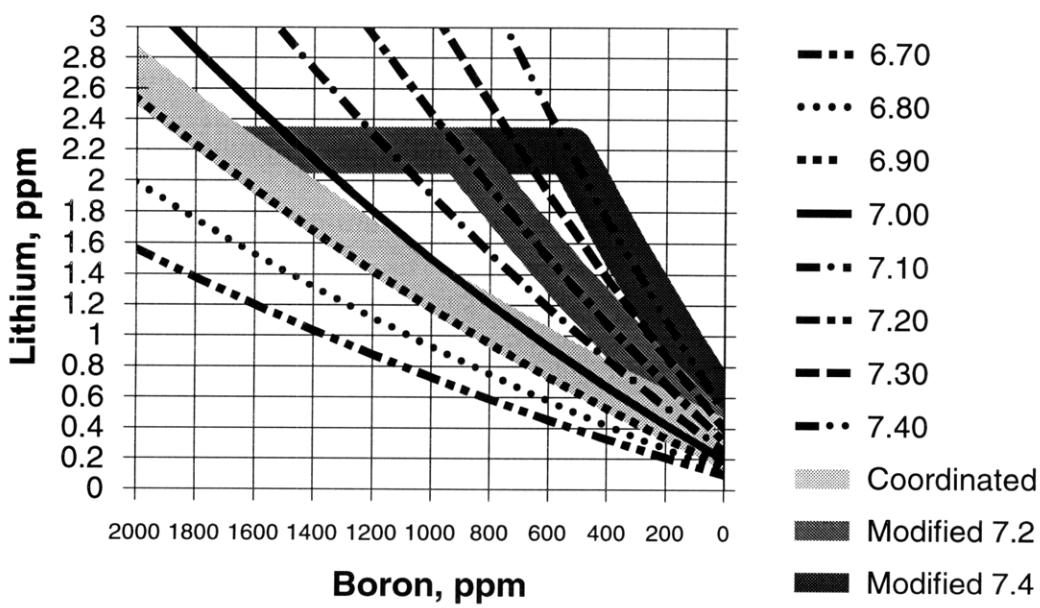
1. Operate at or above pH = 6.9 to minimize CRUD deposition on fuel and CRUD-enhanced Zircaloy corrosion

2. For operation above 2.2 ppm lithium for extended periods of time (>3 months) to achieve a pH = 6.9 during an extended fuel cycle, a plant specific fuel and materials review should be performed. Prolonged exposure to elevated concentrations of lithium raises concerns about PWSCC and Zircaloy corrosion.

3. Once lithium has been reduced to 2.2±0.15 ppm (consistent with 1 and 2 above) either maintain pH constant at 6.9 (coordinated chemistry regime) or maintain lithium concentration constant at 2.2±0.15 ppm (modified chemistry regimes) until a specified pH between 6.9 and 7.4 is reached.

4. Maintain selected pH while controlling lithium to ±0.15 ppm until the end of the operating cycle.

Figure 2-11: Relationship between Boron, Lithium, and pH Levels for the Case Study PWR (at Tave = 311.86)



From Figures 2-10 and 2-11, the higher boron concentrations necessary to run at extended operating cycles force plants to use lithium levels at or near the 2.2 ppm limit. While this limit is not violated explicitly with extended cycle operations, operating at lower levels of lithium would certainly be desirable. Further, recent industry experience has shown that CRUD deposition is not mitigated significantly enough by adhering to a lower pH limit of 6.9 [C1,S4]. Since maintaining a high enough beginning-of-cycle (BOC) pH is the essential element to reducing CRUD deposition, higher levels of lithium will be needed to maintain a higher level of pH at BOC for all plants [N4]. Consequently, the consistently higher boron concentrations associated with extended operating cycles will have a negative effect with respect to waterside corrosion.

With this problem, there are three alternatives: (1) keep boron levels as low as possible, evaluate the effects of higher lithium levels on plant performance, and then act once more information is known about how the specific plant reacts, (2) develop materials that can be used within the primary system that are more resistant to corrosion and the effects of lithium while retaining the positive attributes of existing components, or (3) use enriched boron in the coolant. While all three of these solutions are feasible, the first two are time-consuming, expensive, and consequently, problematic. The third, using enriched boron, would provide for more of the neutron absorbing isotopes of boron (B^{10}) in the coolant per acidic cation of H^+, decreasing the amount of lithium necessary to maintain a given pH. While this seems like an easy solution, enriched boron is expensive and can increase the moderator temperature coefficient. Additionally, use of enriched boron to control coolant chemistry and core reactivity would require its accompanying use in the boron injection tanks maintained for reactivity control in an accident scenario, incurring additional costs and requiring a change in operating practice. However, should these water chemistry issues become a problem for extended cycle operations, use of enriched boron may be the best solution.

2.3.4 Axial Offset Anomaly (AOA)

For PWRs, another issue that is a corrosion and water chemistry related phenomenon is that of Axial Offset Anomaly (AOA). Axial offset is a metric used to measure axial power peaking and is defined as the difference between the sum of the normalized axial powers at the nodes in the top half of the axial power distribution and the sum of the normalized axial powers at the nodes in the bottom half of the axial power distribution, all divided by the number of nodes in the axial power distribution. Defined as the difference between predicted and actual axial offset, AOA is believed to be caused by boron hideout in CRUD deposits on fuel rods; however, this phenomenon is currently not well understood. AOA is predicted to increase with cycle burnup, which will certainly present problems for extended operating cycles. AOA has also been found to be problematic for high temperature plants, especially where there is high power peaking and nucleate boiling [R3]. This supports the idea that this effect will be more of a problem for extended cycles, since some extended cycle fuel will be in hotter regions of the core for long periods of time.

AOA is undesirable because it can increase local power peaking, which will affect fuel thermal performance adversely. The concerns about AOA are similar to those of rod bowing and axial growth, discussed in Section 2.7. Since CRUD deposition can be mitigated with a carefully controlled water chemistry strategy, AOA might also be minimized by such an approach. However, this phenomenon is not well understood at this time.

2.4 Rod Internal Pressure

Keeping the rod internal pressure below nominal system pressure is a concern because this effect can be a contributing factor to the loss of cladding integrity. Figure 2-1 shows that this concern is one of eight direct factors which can contribute to the stress and strain of the cladding, which is also affected by rod internal pressure indirectly via hydride reorientation. With this criterion, there are two main concerns, centered around thermal and mechanical criteria, respectively [E1]:

(1) that the cladding creep away from the fuel from a rod internal pressure above system pressure does not result in a lower gap conductivity, increasing temperatures and fission gas release, i.e. a thermal feedback effect

(2) hydride reorientation within the Zircaloy does not result in the loss of ductility and lead to brittle fracture

2.4.1 Thermal concerns

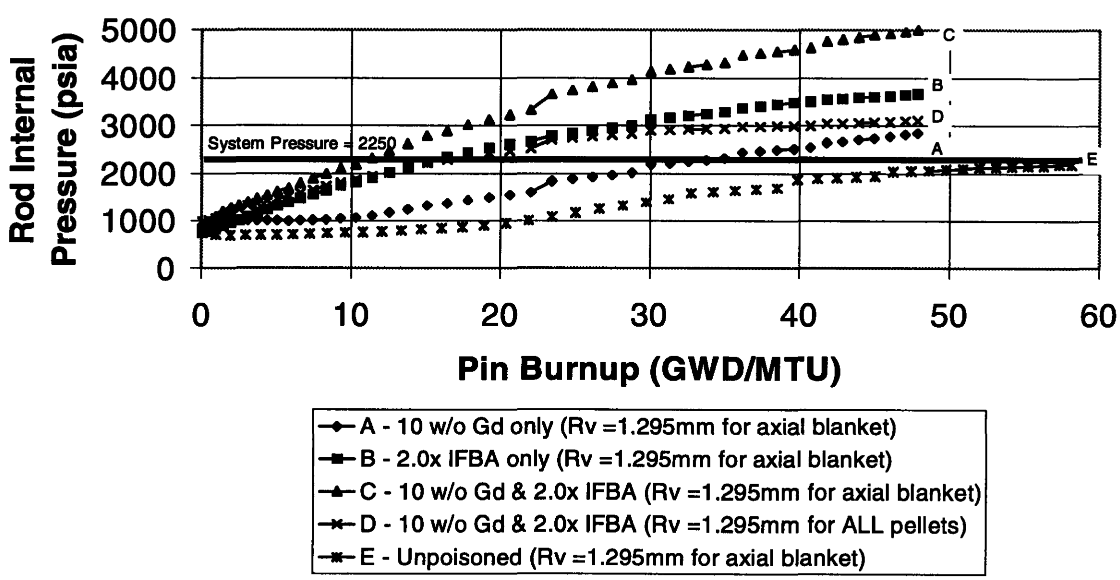
As uranium fissions, it creates fission products, some of which are gaseous and are trapped in the UO_2 fuel lattice. As the operating temperature of the fuel rod increases, so does the amount of this gas that is released from the lattice. Extended operating cycles will have an impact on rod internal pressure as some of the fuel pins used in this strategy operate at higher temperatures for long periods of time, resulting in the release of more fission gas from the fuel matrix. This is especially of concern with the poisoned fuel pins used in both the PWR and BWR, as both use high concentrations (12 $^{w}/_{o}$) of Gadolinia, Gd_2O_3. This burnable absorber, which is integrated into the UO_2 fuel pellet, significantly degrades the thermal conductivity of the fuel, resulting in higher fuel pellet temperatures and an increase in the amount of fission gas released. This release of fission gas is undesirable not only because it increases the pressure inside of the rod, but also because the two main types of fission gas released, Xe and Kr, have much lower thermal conductivities than the original fill gas, He.

For the case of the PWR, the fuel rods containing burnable absorbers also use Westinghouse's IFBA (Integral Fuel Burnable Absorber), a thin coating of zirconium di-boride (ZrB_2) that is sprayed on the outside of the fuel pellets containing the Gd_2O_3- UO_2 mixture. When the neutron absorbing B^{10} isotope in the IFBA absorbs a neutron, it undergoes the following (n,α) reaction:

$$B_5^{10} + n_0^1 \rightarrow \alpha_2^4 \uparrow + Li_3^7 \qquad \{2\text{-}3\}$$

While this increase in the amount of helium (α) gas in the pin helps the thermal conductivity of the fill gas, it hurts the overall fuel performance because it increases the rod internal pressure.

Figure 2-12: Effect of Burnable Absorbers on Rod Internal Pressure for the Case Study PWR Extended Cycle Envelope Pin



To show the effects that these different burnable absorbers and their combination will have on rod internal pressure, Figure 2-12 shows the results of an analysis of rod internal pressure over pin-life performed on an early iteration of a limiting fuel pin in an extended core design for the case study PWR.

From this figure, two main conclusions can be drawn. First, the higher internal pressures experienced by the poisoned pins are due mainly to the use of IFBA in the fuel; high concentrations of gadolinia do not have as appreciable an effect. Since the IFBA used in the above figure is at a concentration of 3.09 mg B^{10}/inch (2.0x), reducing this concentration would decrease the amount of helium produced in the (n,α) reaction and subsequently decrease the rod internal pressure of the fuel pin. Second, by increasing the plenum volume within the fuel rod by using annular fuel (Case D), the rod internal pressure can be significantly decreased.

These findings were instrumental in helping to establish a technically feasible extended cycle core design, taking into account these special concerns for fuel pins containing burnable absorbers. For the case study PWR, a decreased amount of IFBA was used (1.0x or 1.545 mg B^{10}/inch), the gadolinia concentration increased slightly to 12 $^{w}/_{o}$ (for neutronic design reasons), and annular fuel was used throughout the entire fuel pin to increase plenum size. Similarly, for the BWR, all of the poisoned fuel pins use annular fuel to provide an increased fuel pin plenum. IFBA is not used in the extended cycle BWR core design because of its detrimental effect on rod internal pressure and because gadolinia was found to be the preferred burnable absorber for several neutronic reasons [M2].

Figures 2-13 and 2-14 compare the rod internal pressures of the extended and reference cycle unpoisoned and poisoned pins, respectively, for the case study BWR over pin life. While there is a slight increase in rod internal pressure for both cases over the life of the pin, these pressures are well below system pressure (by more than a factor of two), satisfying the prescribed criterion and leaving a large margin for fission gas release under transient conditions. The slight increase in rod internal pressures witnessed in these results is consistent with the envelope pin power profiles shown in Figures 1-6 and 1-7.

While there is adequate margin for rod internal pressure for the BWR envelope pins, the PWR envelope pins present greater challenges to this criterion, as shown in Figures 2-15 and 2-16. The limit that these pin pressures are normally evaluated against is 2800 psia; this is the actual limit used by Westinghouse for this particular fuel design which accounts for the cladding-fuel differential growth and hydride reorientation criteria discussed at the beginning of this section [R1, W1].

Figure 2-13: Comparison of Rod Internal Pressures for the Unpoisoned Envelope Pins for the Case Study BWR

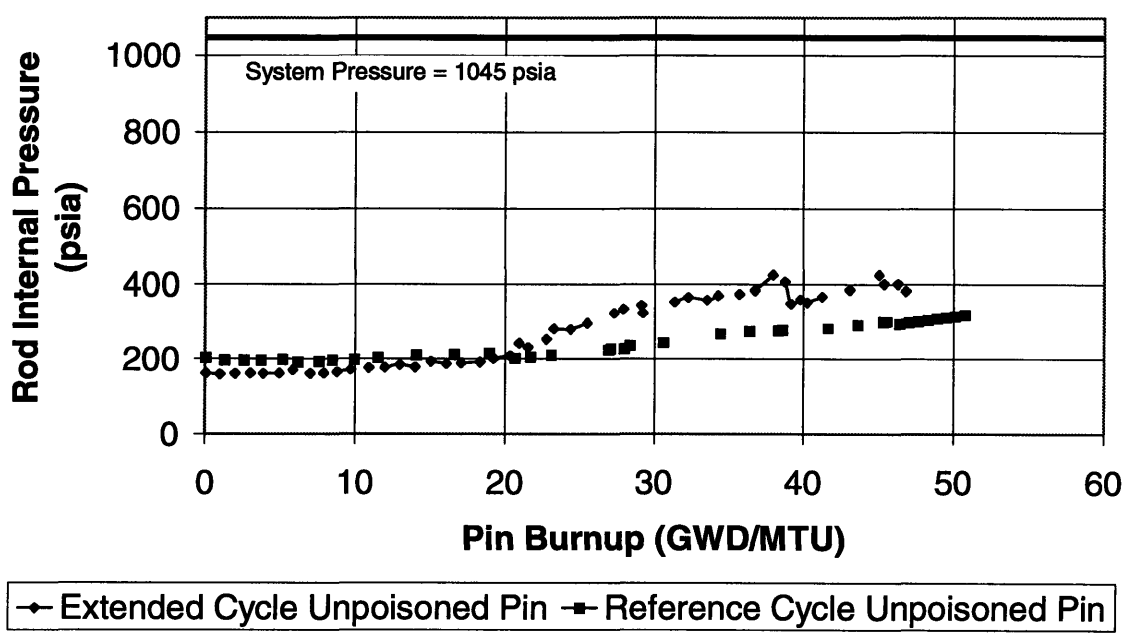
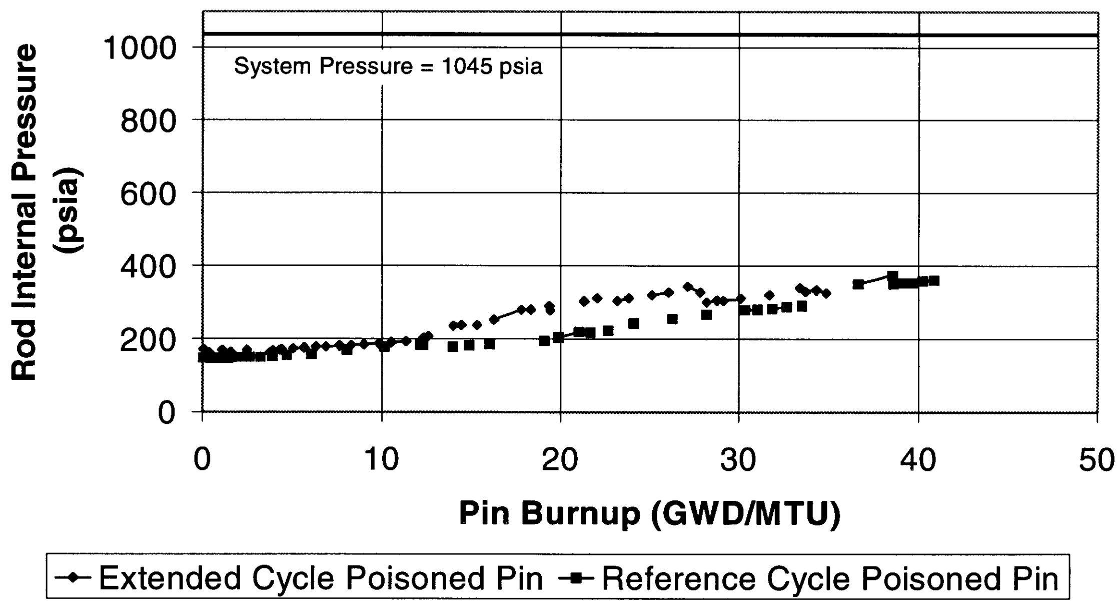


Figure 2-14: Comparison of Rod Internal Pressures for the Poisoned Envelope Pins for the Case Study BWR



Since this report is focused on steady state analysis and rod internal pressure will certainly increase under transient conditions (since increases or spikes in power will result in higher temperatures and more fission gas being released), a margin of 200 psia is used to account for transient effects, resulting in a limit of 2600 psia for the PWR extended cycle fuel pins. However, it should be noted that this margin is based on engineering judgment and must be confirmed through the transient analysis that needs to be done in order to confirm the technical feasibility of extended operating cycles.

Both the extended cycle poisoned and unpoisoned pin meet this criterion, with the extended cycle poisoned envelope pin showing a pressure history similar to that of its reference cycle counterpart. The effect of the extended cycle poisoned pins on rod internal pressure is not as severe as it was with the temperature related criteria evaluated earlier (fuel centerline temperature, clad-oxide interface temperature) because the only change that has been made from the reference cycle poison pin is that Gadolinia and an increased enrichment have been added. Since the extended cycle pin runs at comparatively lower powers at the beginning of pin life (shown in figure 1-8) and the effects of Gadolinia have been shown to be comparatively benign to those of IFBA with respect to rod internal pressure (shown in Figure 2-12), this similarity is understandable.

Figure 2-15: Comparison of Rod Internal Pressures for the Unpoisoned Envelope Pins for the Case Study PWR

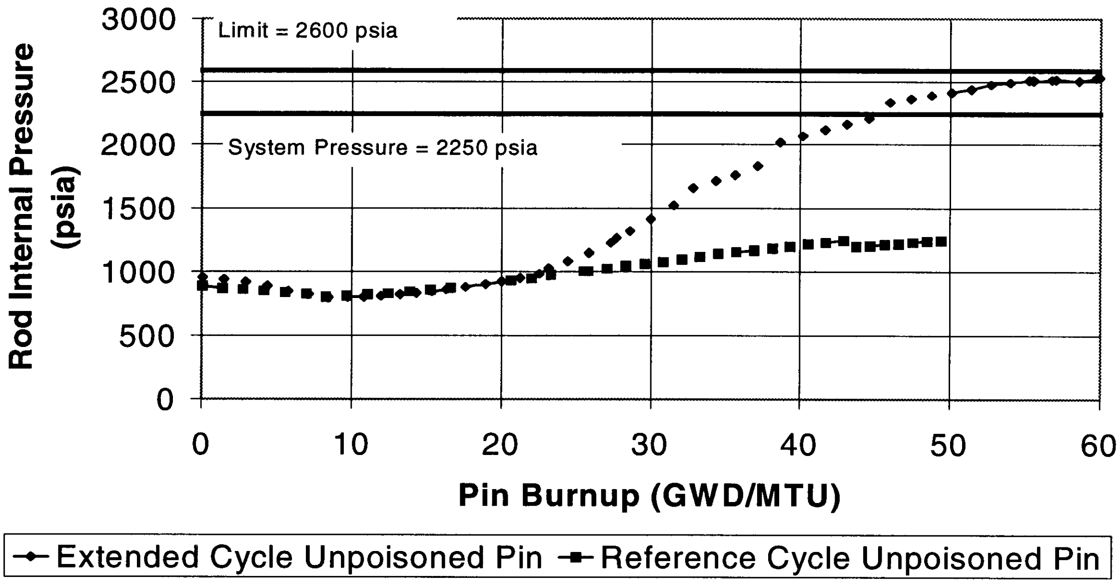
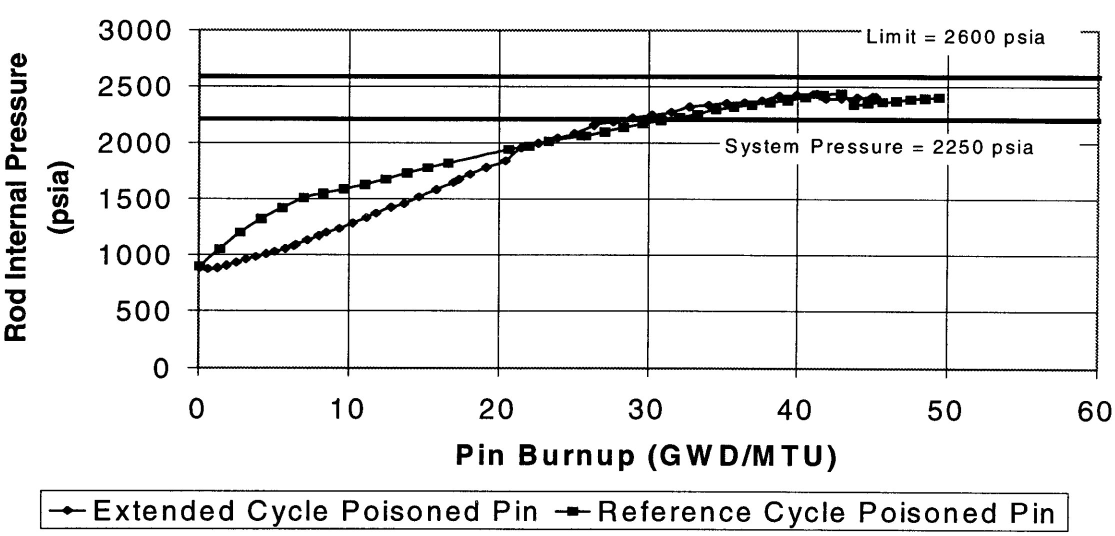


Figure 2-16: Comparison of Rod Internal Pressures for the Poisoned Envelope Pins for the Case Study PWR



The extended cycle unpoisoned pin experiences pressures greater than its reference cycle counterpart over the life of the pin. This can be explained by the fact that the extended cycle pin has a higher enrichment (by ~2.6 $^{w}/_{o}$) and consequently runs at consistently higher powers (as shown in Figure 1-8), releasing more fission gas and increasing rod internal pressure.

While the extended cycle poisoned and unpoisoned pins for the case study PWR meet the established criterion for rod internal pressure, they do so with little margin. However, the extended cycle poisoned pin has a pressure history very close to that of the reference cycle poisoned envelope pin, indicating that the prescribed margin is adequate since the reference cycle has been approved through the licensing process and proven in actual plant operation. Should more margin be required, one possible solution is to use fuel assemblies with a greater number of fuel pins, decreasing the power generated per pin and consequently, the rod internal pressure. However, in order to implement this solution the upper core internals of the case study PWR would need to be modified and an extensive licensing and safety analysis would need to be performed, resulting in an additional cost. Annular pellets in the unpoisoned fuel pins could also be used to help alleviate the effects of rod internal pressure.

2.4.2 Mechanical concerns

The second of the reasons listed for looking at rod internal pressure is hydride reorientation within the Zircaloy cladding. While this is hard to evaluate quantitatively given the tools and time that are available for this report, a qualitative assessment can be made with regard to this effect.

During irradiation, stresses will exist in the cladding of a rod-type fuel element. These stresses will be produced by differential thermal expansion between the cladding and the fuel and by rod internal pressure build-up. Tensile stresses will exist in the outer part of the cladding, while compressive stresses will exist in the inner part of the cladding. When hydrides precipitate while the cladding is subject to an applied stress greater than 5000 psi, the platelets tend to precipitate perpendicular to tensile stresses (radially) and parallel to compressive stresses (circumferentially). Given that precipitation occurs preferentially in colder, outer regions of the cladding and that the outer regions are subject to increasing tensile stress with increasing rod internal pressure, more hydrides will precipitate in the cladding outer region and will tend to be oriented radially, normal to the primary hoop stress. This radial orientation serves to reduce the ductility of the cladding and may cause cladding to fail at lower stresses and strains than predicted [L1,P3]. The higher rod internal pressures shown to exist for extended operating cycles will certainly have an effect on this parameter, as more hydrides (of those that have precipitated) will be reoriented undesirably. This effect will vary in magnitude, just as the increase in rod internal pressure varies for each case explored in the last section. However, as discussed earlier, the higher temperatures at which these extended cycle pins run will cause less hydrides to precipitate during operation than with current practice; thus, less hydrides will reorient and extended operating cycles may be better off when running at full power. Unfortunately, shifts in power, such as for outages in both kinds of LWRs and for control rod movement in BWRs, will cause the hydrogen picked up by extended cycle pins to precipitate. Since extended cycle pins will pick-up more hydrogen over pin-life due to higher power operation, more hydrogen will precipitate and extended cycle pins will be at an inherent disadvantage with respect to structural integrity.

Deformations and manufacturing method of the cladding also have an effect on hydride orientation [P3]. This may be advantageous to longer cycles as there is less of a chance for fuel damage from handling during outages. However, there is a trade-off, as hydrides will preferentially orient parallel to a local deformation, should they form. With damaged fuel used in extended cycles, hydrides may orient radially because of the defect, regardless of the effects of rod internal pressure and associated stress reorientation. Given the longer in-core residence time without shuffling, fuel cannot be monitored and/or changed to prevent this effect.

2.5 Fuel mechanical performance

2.5.1 Design stress and strain

With respect to fuel mechanical performance, cladding design stress and strain are important criteria to be measured. Factors which contribute to these elements and must be considered in an evaluation include rod internal pressure (hydride reorientation), waterside corrosion, Pellet Clad Mechanical Interaction (PCMI), thermal creep, irradiation induced creep, and rod bowing resulting from irradiation enhanced growth of Zircaloy cladding.

The limits prescribed to evaluate the design stress and strain of a fuel rod are "stress, strain, and loading limits for…fuel rods…should be provided. Stress limits that are obtained by methods similar to those given in Section III of the ASME Code are acceptable." [N1] The ASME Code that is referred to is the Boiler and Pressure Vessel Code and the particular part of Section III that is of importance is Article III-2000:

"Design Stress Intensity Values for Class 1 Components" [A1]. The stress limits that are outlined in the Code are based on the maximum shear stress theory, which uses a stress intensity, defined as the largest algebraic difference between any two of the three principal stresses, as a limit. This stress intensity must not exceed the lowest of the following primary stress limits [A1]:

1. one-third of the specified minimum tensile strength at room temperature ($1/3\sigma_{uRT}$)
2. one third of the tensile strength at temperature ($1/3\sigma_{uT}$)
3. two-thirds of the specified minimum yield strength at room temperature ($2/3\sigma_{yRT}$)
4. two-thirds of the yield strength at temperature ($2/3\sigma_{yT}$)

Since the value of both the minimum tensile strength and minimum yield strength will decrease with increasing temperature, considerations 2) and 4) will certainly be most limiting. Additionally, Zircaloy yield strength has been shown to increase with increased radiation exposure, which may cause 2) to be the most limiting [E1].

The three factors that contribute directly to the stresses in the fuel rod are system pressure, rod internal pressure, and the fuel-clad contact pressure. While system pressure does not change for extended operating cycles, the rod internal pressure as well as the fuel-clad contact pressure resulting from PCMI will certainly enhance this effect.

With the impact of extended cycles on the internal pressure having been discussed in the previous section, the fuel-clad contact pressure is also expected to have a deleterious effect on fuel performance for extended cycles. Since some fuel is hotter for a long period of time, fuel pellet growth will be enhanced in extended operating cycles, as this is a temperature dependent phenomenon [S2]. Because this fuel pellet growth will be greater than the rate at which cladding dimensions are changing from rod internal pressure and thermal and irradiation induced creep, greater fuel-clad contact pressure and hence, greater stresses, will exist within extended cycle fuel rods.

Waterside corrosion and rod bowing both serve to weaken the structural integrity of the fuel rod and consequently, reduce the stress at which the rod will fail and contribute to the stress and strain, respectively. The corrosion reaction used as the basis for discussion in Section 2.3 causes the zirconium in the cladding to form a weaker, insulating layer of ZrO_2. Concurrently, the cladding is picking up hydrogen, which weakens the ductility of the cladding when it precipitates and reorients. Since the corrosion effect was shown to be enhanced appreciably for the extended cycle PWR and only slightly for the extended cycle BWR, this corrosion effect will more significantly degrade the structural integrity of the fuel rod for this scenario. The higher rod internal pressures associated with extended cycles will re-orient more precipitated hydride platelets, further reducing the stresses that a fuel rod can withstand before failing. Rod bowing due to irradiation-induced axial growth of the fuel rods will also lower the design stress limit as bowing increases stresses present in the fuel rod; this effect will be discussed in more detail in Section 2.7.

Strain limits have also been defined in accordance with Refs [A1] and [N1] as "the total mean circumferential strain shall not exceed 1% for steady state conditions" [E1]. Thermal and irradiation induced creep, which are functions of the hoop stress, yield stress, and time of exposure, will have a greater effect on strain values in extended operating cycles. Since fuel pins in an extended operating cycle will be exposed to higher hoop and yield stresses for longer periods of time, these two effects will certainly exacerbate the contributing effects to cladding strain, and result in a decreased margin to failure.

2.5.2 Fatigue cycling

While design stress and strain are obvious mechanical design concerns, fatigue cycling of the cladding needs also to be considered. This is because the conventional yield strength as determined from the usual tensile test is not always the value that best represents the behavior under cyclic conditions. To this end, a safety factor of 2 on the stress amplitude and 20 on the number of cycles is applied to the cumulative number of strain fatigue cycles over the lifetime of the fuel rod [O1]. This factor may be less of a concern for extended operating cycles, whose fuel experiences less shifts in power by virtue of the shorter in-core residence time and which avoids more of the largest changes in power due to outages. Additionally, this will be more of a concern for the case study BWRs, which will experience more frequent power shifts, hence, more thermal and mechanical cycles, than the case study PWR.

Fatigue cycling also has a pronounced effect on re-orientation of hydride platelets that have precipitated in the cladding [M1, P3]. Large stresses must accompany cycling for it to have an aggravating effect. Since the stresses predicted to exist for extended operating cycles are greater than those for current practice, fatigue cycling will certainly be more of a concern for this new operating strategy with respect to hydride re-orientation. However, since the length of the hydrogen platelet also affects the ductility of the cladding and large stresses and number of cycles have been shown to decrease the size of the hydride, a competing effect exists between smaller, re-oriented platelets and larger, preferentially oriented ones with respect to fatigue cycling and its effect on extended cycles.

2.6 Fretting

The largest cause of fuel failure in U. S. nuclear power plants today is fretting [R2]. Fretting can be categorized as debris fretting, caused by foreign objects introduced into the reactor coolant system during outages, and grid-to-rod fretting, caused by the relative motion between the fuel rod and the fuel assembly. Hard to evaluate quantitatively, the only prescribed limits that exist with respect to this criterion is that "fretting...should be limited." [N1].

Debris fretting would probably be less of a problem for extended operating cycles, since the reactor vessel head is removed less often. However, there is a trade-off as plants might no longer be able to "ride out" a failed fuel rod until the next outage with extended operating cycles and a costly forced outage may result. Grid-to-rod fretting can be eliminated with improvements in fuel assembly design, as has already been shown by several fuel vendors, and consequently is not a concern with extended operating cycles [R2]. Overall, fretting is hypothesized to be less of a problem for the case study BWR as compared to the case study PWR since lower (liquid) flow rates are used.

2.7 Rod bowing and axial growth

Rod bowing, which is caused by irradiation growth of the cladding and the hydraulic forces associated with the flow of the coolant, could prove uniquely problematic for extended operating cycles. Again, vague limiting parameters have been established for this criterion: "dimensional changes such as rod bowing or irradiation growth of fuel rods...should be limited" [N1]. While this is a hard factor to evaluate quantitatively, fuel assemblies will not be rotated as often or shuffled to cancel the differential Zircaloy growth that fuel rods with a prolonged exposure to a flux gradient will experience or the asymmetric hydraulic forces that can contribute to rod bowing. Thus, single batch extended cycles will certainly prove more problematic in this area. This is supported by evidence that this is a pressing issue for the NRC with current operating cycles. The NRC issue centers around safety with respect to both control rod drop times and the potential for control rods to not fully insert [N3]. If these problems exist for current operating cycles that shuffle their fuel, extended operating cycles will certainly prove challenging in this area. Rod bowing is also a concern because it affects local power peaking, a concern for all of the thermally related fuel performance factors, and increases the stresses in certain areas of the fuel rod.

While axial growth and rod bowing are related phenomena for the case study PWR, the case study BWR concern over axial growth is one of loss of fuel configuration. The PWR rod-to-tie plate gap is reduced with burnup, and if closed, can result in rod bowing and possible damage. However, the BWR rod-to-tie plate spacing increases with burnup so that the end cap shank of the fuel rods can become disengaged from the tie plate, resulting in a loss of fuel configuration. The increase in the rod-to-tie plate spacing is due to the growth rate of the tie rods that connect the upper and bottom tie plates being greater than the growth rate of the BWR fuel rods [E1]. Thus, axial growth and rod bowing are concerns for the both of the case study LWRs, but different reasons apply.

2.8 Summary

Extended operating cycles will pose unique challenges to fuel performance in the extended cycle LWR core designs with respect to the six of the eight issues identified earlier, stemming mainly from the fact that fuel stays in one place for a longer period of time and runs at higher pin powers over part of pin life than with current practice. These factors are: (1) design stress and strain, (2) fatigue cycling, (3) fretting, (4) waterside corrosion, (5) rod bowing/axial growth, (6) rod internal pressure. While within design limits for steady state operation, extended operating cycles degrade the thermal margin available for transient effects with respect to (9) clad overheating (for the case study PWR; the effects for the case study BWR could not be accurately determined) and (10) fuel centerline melt; however, the ample margin available for the latter of these two factors alleviates any concern over degradation due to extended cycle operation. With extended cycles, some of these fuel rods will be in higher power regions of the core and since many of the above issues are temperature related or driven and these rods will not be shuffled, fuel performance may be negatively affected. Further, a change in one of the factors will have an effect on most other fuel performance issues, either directly or indirectly, as is illustrated in Figure 2-1. Solutions to mitigate the negative effects of extended operating cycles on nuclear fuel performance were offered as a means of making this new strategy technically feasible.

CHAPTER 3: SUMMARY, CONCLUSIONS, AND RECCOMMENDATIONS

3.1 Summary and conclusions

Steady state fuel performance was examined in this report in view of its importance to the technical feasibility of extended operating cycles,. The importance of this facet centers around the fact that the consequences of failed fuel are greater for extended cycle operation than for current practice. Extended cycles offer a unique benefit by running longer without interruption; poor fuel performance, i.e. failed fuel, would degrade this benefit.

The issues in this report were assessed only at the steady-state level, as a foundation for the consideration of Anticipated Operational Occurrences (AOOs) and transient conditions, which are certain to present greater challenges to nuclear fuel performance due to their more severe conditions. Even at this preliminary steady state level, extended cycle operation was found to exacerbate several fuel performance issues, resulting mainly from the fact that fuel in an extended operating cycle is operated at higher powers over part of the core life and does not have the benefit of shuffling.

In order to accurately quantify the fuel performance effects of extended cycle operation, a pseudo or "envelope" pin was created, which represented the operating characteristics of the highest power fuel rod in the core at a given pin burnup step. This envelope pin was created for both extended cycle and current practice, so that extended cycle results could be compared to both existing licensing limits and current practice. While this approach is somewhat conservative, it is the simplest way to evaluate fuel performance in an extended cycle core where the limiting fuel rod changes location often and fuel rods generically operate at higher powers for prolonged periods of time. This envelope pin approach was used to compare extended operating cycles through both their power profiles (Chapter 1) and output from a state of the art fuel performance computer code (Chapter 2) which used the envelope pin information as an input (see Appendix A).

The US Nuclear Regulatory Commission's Standard Review Plan's Sections 4.2 and 4.4 were used as the basis for the criteria that should be evaluated in this report, since these are the relevant sections of the document that prescribes the licensing limits and criteria for nuclear fuel designs. From this document, ten steady state fuel performance issues were identified: (1) stress and strain, (2) fatigue cycling, (3) fretting, (4) waterside corrosion, (5) axial growth and rod bowing, (6) rod internal pressure, (7) primary hydriding, (8) cladding collapse, (9) cladding overheating, and (10) fuel centerline melt. Of these ten issues, (7) and (8) were found to not be uniquely affected by extended cycle operation, (1) and (2) were hypothesized to have greater effects in BWRs and (3) was hypothesized to have a greater effect in PWRs.

The eight issues that were found to have unique effects with respect to extended cycle operations were subsequently evaluated. Table 3-1 lists these issues, their prescribed limits, relevant results, whether the issue is inherently more problematic for BWRs or PWRs, and a proposed solution, where applicable. Further, the solution of increasing the number of fuel pins per assembly, thereby decreasing LHGRs and concerns associated with temperature and power driven phenomena, would help mitigate many extended cycle fuel performance issues. This solution also holds promise for fuel designs for extended burnup operating strategies, which are predicted to face similar power and temperature driven performance issues [F1, W2]. Additionally, an increase in the number of rods per assembly would decrease the stored energy per fuel rod,

Table 3-1: Summary of Unique Fuel Performance Effects on Extended Cycle Operation

	Prescribed limit [N1]	Extended Cycle Result	Reference Cycle Result	More problematic for BWR or PWR?	Proposed solutions
(1) Stress and strain	"limits...should be provided"	Predicted to be worse	N/A	BWR	A
(2) Fatigue cycling	"should be significantly less than the design fatigue lifetime"	May have an inherent advantage	N/A	BWR	N/A
(3) Fretting	"should be limited"				
- debris		Uncertain; competing effects	N/A	Indifferent	Increased awareness during outages
- grid-to rod		Not a concern	N/A	PWR	Improved assembly grid design
(4) Waterside Corrosion	"should be limited"	[redacted]			Water chemistry control; A; development of improved cladding alloys; annular fuel pellets
- oxide layer	80 microns*	BWR - may be better off PWR - uncertain; competing effects	N/A	Indifferent	
- secondary hydriding		BWR - may be better off PWR - uncertain; competing effects	N/A	Indifferent	
- CRUD deposition		Predicted worse	N/A	Indifferent	
(5) Rod bowing/ axial growth	"should be limited"	Predicted worse	N/A	Indifferent	Currently unidentified
(6) Rod internal pressure	"nominal system pressure unless otherwise justified" P_{sysB} =1045 psia P_{sysP} =2250 psia P_{limP} =2600 psia*	BWR- 400 psia (P) 400 psia (U) PWR - 2400 psia (P) 2500 psia (U)	BWR- ~ 400 (P) ~ 300 (U) PWR - 2400 psia (P) 1250 psia (U)	Indifferent	Change in burnable absorber loading; annular fuel for poisoned pins; A.
(9) Cladding overheating	"should be prevented"	Steady State CHF within design envelope Transient BWR - uncertain PWR - degraded thermal margin	N/A	Uncertain	None necessary
(10) Fuel centerline melt	"is not permitted"	Within envelope	Within envelope	Indifferent	None necessary; A

* - limit developed specifically for this report
A - increase in the number of fuel pins per assembly
P - poisoned pins
U - unpoisoned pins

decreasing the effect of AOOs and transients on fuel integrity. While this solution can be readily implemented in existing BWRs, the upper internals of PWRs would need to be modified to accommodate such a fix. Annular fuel pellets may also be helpful in mitigating some of the undesirable fuel performance effects of extended operating cycles. However, this solution would require either a higher enrichment to maintain cycle length (incurring additional costs and neutronic design problems) or a penalty in operating cycle length, because of the mass of fuel that is removed from the pins.

Note that while feasible solutions seem to exist to almost all of the issues that present challenges to technical feasibility, the problem of rod bowing and axial growth appears to be the largest impediment to implementing extended cycles because a solution to this problem is not readily apparent.

3.2 Recommendations for future work

Since only a preliminary analysis of the steady state fuel performance issues associated with extending operating cycles has been made, a detailed evaluation using more advanced tools, i.e. computer codes, should be performed to assess those factors which could only be addressed qualitatively at this stage. Additionally, a prediction of how fuel in this new operating strategy would behave under AOO and transient conditions should be made to complete the assessment of technical feasibility.

Given that rod bowing and axial growth are problems with no readily apparent solution, research should be conducted in these areas to determine if a viable solution exists. Further, the feasibility and performance of fuel assemblies with an increased number of fuel pins and fuel pins with annular pellets should be assessed to determine if either is a preferred way of mitigating fuel performance problems for extended cycle operation.

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Appendix A: Integrated Process for Achieving Quantitative Results

In order to obtain the quantitative results for the fuel performance analysis conducted in this report, an integrated process using two computer codes and the envelope pin method described in Chapter 1 was necessary. A brief description of this process follows.

First, neutronic models of the extended and reference cycle cores were developed using the CASMO/TABLES/SIMULATE-3 software suite, in conjunction with the core design research for the extended cycle project (see Ref [M2]). Once the four models for the case study BWR and PWR reference and extended cycle cores were finalized, information was extracted from these designs to construct the power histories of the envelope pins. Specifically, the highest axially-averaged power poisoned and unpoisoned pins in the core were identified at each cycle burnup step. The following parameters were recorded at each cycle burnup step for each of the eight envelope pins that were created using this method (poisoned or unpoisoned, reference or extended cycle, case study BWR or PWR):

Table A-1: Key Input Information for the Fuel Performance Analysis

Case Study BWR[1]	Case Study PWR
(a) Pin Relative Power Fraction (RPF[2])	
(b) Axially averaged pin burnup	
(c) Pin Axial flux profile	
(d) Core Flow (%)	
(e) System Pressure	
(f) Core Inlet Temperature	

This information was then used to: (1) construct the eight envelope pin profiles used as the basis of this analysis (using items (a) and (b)) and (2) construct input decks for the state of the art fuel performance code FROSSTEY-2 (Fuel **RO**d Steady-State Thermal Effects) used in this analysis (using items (a) through (f)). Other vendor specific information, such as fuel and cladding dimensions, cladding materials properties, etc. was also necessary to construct the input decks for FROSSTEY-2 and was obtained from contacts in industry.

Once the input decks were constructed, FROSSTEY was run to predict the rod internal pressures and fuel rod temperature distributions that existed during steady state operation. These results were used for the quantitative analyses found in Chapter 2.

[1] The three pieces of information listed only for the case study BWR were recorded at each burnup step because FROSSTEY requires this as input information for BWRs. These values stay constant over core (and pin) life for the case study PWR.

[2] Defined as ratio of the axially averaged linear heat generation of the pin to the core average linear heat generation rate; also known as $F_{\Delta h}$ for PWRs.